Reclamation of Fly Ash Lagoons: An Ecological Approach

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Abstract

Coal combustion for electric power generation produces large amounts of solid residues of which fly ash is the major portion. The physical and chemical properties of fly ash collected from Tsang Tsui fly ash lagoon had been examined as compared to raw fly ash from the electrostatic precipitator and a garden soil. Vegetation composition on a fly ash lagoon was also investigated. Lagooned fly ash was loamy in texture with bulk density, porosity and saturation capacity of 0.88 g/cm^3, 88% and 56% respectively. High penetration resistance of lagooned fly ash (985 Kpa) was observed, showing that vertical root growth in the fly ash lagoon would be inhibited. The lagooned fly ash was alkaline with very high concentration of soluble salts (120 mS/cm) which may be attributed to the use of seawater as transporting medium of fly ash. The concentrations of organic C and N of fly ash were low while that of B (17.5 μg/g) reached the toxic level to most plants. In total twelve plants species were sampled of which *Leptochloa fusca*, *Frimbristylis polytrichoides* and *Tamarix chinensis* ranked the top three in terms of importance value.

A tree planting trial was conducted in pots in a greenhouse in which plant survival rate and growth rate were compared with those grown on a garden soil. Of the twenty five tree species tested, only five species survived at the end of the trial, namely *Melaleuca leucadendron*, *Leucaena leucocephala*, *Casuarina equisetifolia*, *Cerbera manghas* and *Hibiscus tiliaceus.* It seems that halophytic plants would be promising for growing on fly ash lagoons although further investigation in the field would be needed.

In another pot trial, no plant growth was observed on lagooned fly ash even with fertilizer applied unless it had been washed. This suggests that toxicity probably

due to high salt and B contents would be the limiting factor for plant growth. When the lagooned ash had been washed, plant growth was enhanced by addition of nutrients especially N and P.

In a column leaching study on lagooned fly ash, different amounts of water (0 mm - 800 mm) were applied to columns. The salts (measured as electrical conductivity) were reduced (< 5 mS/cm) and distributed evenly along the column after 200 - 400 mm leaching water was added. The B content was also reduced by leaching (about 4 μg/g on the surface ash after 200 mm water leached) but the removal rate was lower than that of soluble salts. Ash from the surface 5 cm which had been leached with different amounts of water was repotted for plant growth bioassay using *Lolium perenne*. No plant growth was observed for ash with less than 80 mm water added. As the leaching rate increased, the dry matter yield of the plant increased accordingly, showing a strong negative correlation to soluble salt and B contents of the fly ash.

In another greenhouse pot trial, lagooned fly ash leached by water (equivalent to 200 mm) was amended with different organic materials namely sewage sludge (SS), pig manure compost (PMC), horse manure compost (HMC) and spent mushroom compost (SMC) in two application rates (50 and 100 tonnes/ha). Plant dry weight was the highest in the 100 SMC treatment followed by 50 SS, 50 PMC > 50 SMC, 100 PMC > 100 SS, 50 HMC, 100 HMC (in descending order). Incorporation of organic wastes to ash enhanced not only plant growth but also foliar nutrient (N and P) contents. However, toxicity problems (probably high salts and B) still existed as shown by the lower dry yield when compared to plant grown on garden soil.

撮要

燃煤發電廠所產生的固體廢物中，煤灰佔相當大的份量。從位於曾嘴的煤灰湖收集到的飛灰 (下稱湖煤灰或煤灰) 中作物理及化學分析，湖煤灰的土質相等於泥土的「沃土」爲主；體積密度是 0.88 g/cm^3；多孔性 88%；水份飽和度 56%。湖煤灰的滲透阻值相當高 (985 Kpa)，顯示出植物的根部發展會受到影響。煤灰偏鹼性，並含大量鹽份，相信是用海水運送所致。有機碳及氮的份量很少，但硼的份量則相當高，達到對植物有害的程度。植物分佈方面，在煤灰湖上共發現十二種植物；當中以(*Leptochloa fusca*)，多穗飄拂草 *Frimbristylis polytrichoides* 及檉柳 *Tamarix chinensis* 爲主。

在一個溫室植物生長實驗中，挑選了二十五個品種的樹木栽種在湖煤灰中，於實驗結束時只有五個品種能夠繼續生長；包括白千層 *Melaleuca leucadendron*，銀合歡 *Leucaena leucocephala*，木麻黃 *Casuarina equisetifolia*，海芒果 *Cerbera manghas* 及黃槿 *Hibiscus tiliaceus*。在另一個植物生長實驗中，黑麥草 *Lolium perenne* 只能在經洗滌過的煤灰中生長。故此，煤灰所含的有害物質似是限制植物生長的主要原因之一，而且耐鹽性高的植物似較適應在煤灰中生長。

在一個滲濾實驗中，經 200-400 毫米的濾水過的湖煤灰，鹽及硼的含量下降了。當以黑麥草種植在不同程度滲濾的煤灰中，植物的生長程度與湖煤灰所含的鹽及硼成份成反比。

在另一個以黑麥草進行的生長實驗中，四種有機物；包括污水廠淤泥 (sewage sludge)，豬糞堆肥 (pig manure compost)，馬糞堆肥 (horse manure compost)及菌堆肥 (spent mushroom compost)，以每公頃 50 及 100 公噸的份量分別混合於經滲濾的煤灰中。結果發現以每公頃 100 公噸份量的菌堆肥能帶來最高的植物生長量 (以乾重量計)。加入了有機物後，植物中的含氮及磷量也提昇了。不過從整體植物重量也低於生長在一般土壤的植物情況來看，煤灰對植物仍然有一定程度上的毒性。

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1.1.1 **Formation of fly ash**

Combustion of coal in coal-fired power plants produces a variety of residues, including fly ash or pulverized fuel ash (PFA), bottom ash, flue gas desulfurization waste, fluidized bed boiler waste and coal gasification ash. Fly ash constitutes about 70% of the total amount of residues generated (Fulekar and Dave, 1986). This enters the flue gas stream and is collected by emission control devices such as electrostatic precipitators (Fig. 1.1).

1.1.2 **Physical and chemical properties of fly ash**

The physical and chemical properties of fly ash vary and depend on the coal source, conditions during coal combustion, efficiency of emission control devices, storage, handling and degree of weathering. Fly ash consists of small, glassy, hollow particles with particle size range in 0.01 to 100 μm and specific gravities of 2.1-2.6 (Adriano *et al.*, 1980). It is predominantly made up of particles in the silt and clay size range (Rees and Sidrak, 1956), e.g. some ashes had fine sand (26-51%), silt (45-70%) and clay fractions (1-4%) respectively (Townsend and Hodgson, 1973).

Fly ash is considered a ferro-aluminosilicate mineral, with Al, Ca, Fe, K, Na and Si as the predominant elements (Adriano *et al.*, 1980). It contains all naturally occurring elements (Klein *et al.*, 1975) and is enriched in trace elements compared

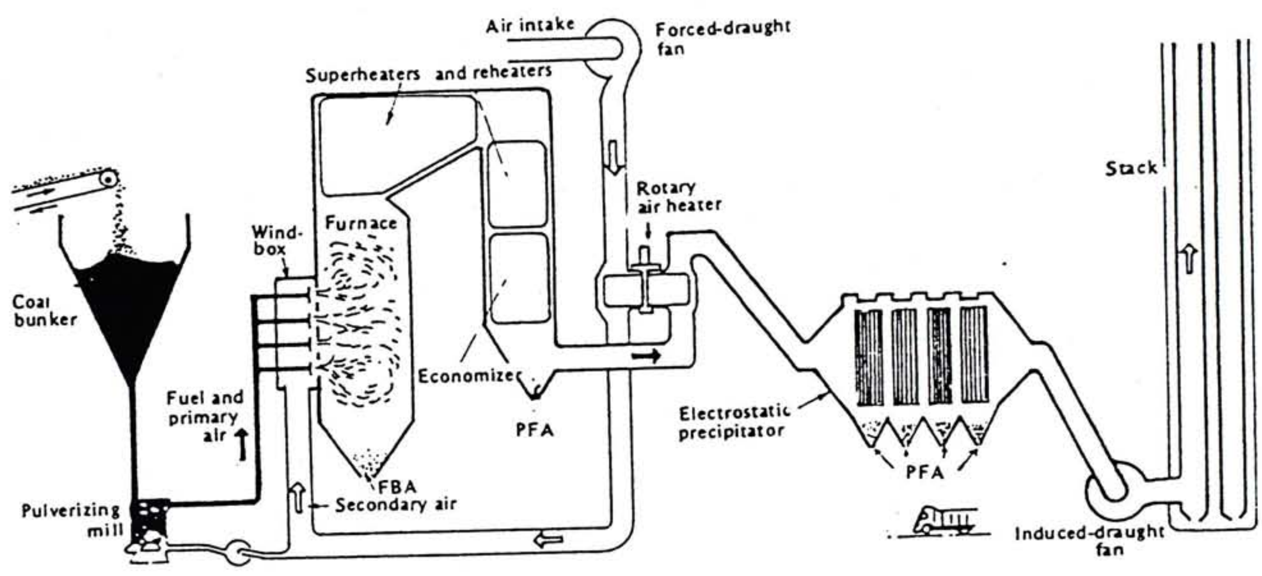

Fig. 1.1 Ash generation at a typical coal-fired station (HEC, 1988).

with the parent coal (Van Hook, 1979; Adriano *et al.*, 1980). Among the elements generally enriched in ashes are As, B, Ca, Mo, S, Se and Sr (Page *et al.*, 1979). As compared with soils, fly ash is low in N (attributed to the loss via volatilization during combustion) but high in most other plant nutrients. Ash pH ranges from 4.5 to 12 depending on the S content of the parent coal (low S content produces alkaline ash). The soluble salt content of fly ash is high but could be reduced by weathering and leaching during lagooning process.

1.1.3 **Disposal**

In the United States, total ash production by electric utilities is estimated at about 67 million tonnes yearly of which 84% is fly ash (Adriano *et al.*, 1980). The industrial utilization of fly ash nowadays become so diversified as for cement making and concrete mixing (HEC, 1988) (Fig. 1.2). However, its utilization was lower than 20% of the total ash produced (Adriano, 1980). The direct reuse of coal ash for all purposes accounts for approximately 25% of the total amount produced (Marlay, 1984). In China, about 75 million tonnes of fly ash are produced each year (Wei *et al.*, 1997). About 7 million tonnes of industrial solid wastes which include coal ash are dumped into rivers, lakes and sea, although a certain fraction is used for the production of industrial materials like cement. Fly ash has also been recycled as a soil amendment, alone or as fly ash-sewage sludge mixture (Page *et al.*, 1979; Adriano *et al.*, 1982; El-Mogazi *et al.*, 1988). Some innovative utilization of fly ash for treatment of polluted waters have also reported (Yadava *et al.*, 1989; Viraraghavan and Rao, 1991; Mott and Weber, 1992) However, since there is no consistent trend of utilization and the demand of ash varied; surplus fly ash becomes a waste disposal problem. This problem is even worse in area where the power plant is remote from industrial area.

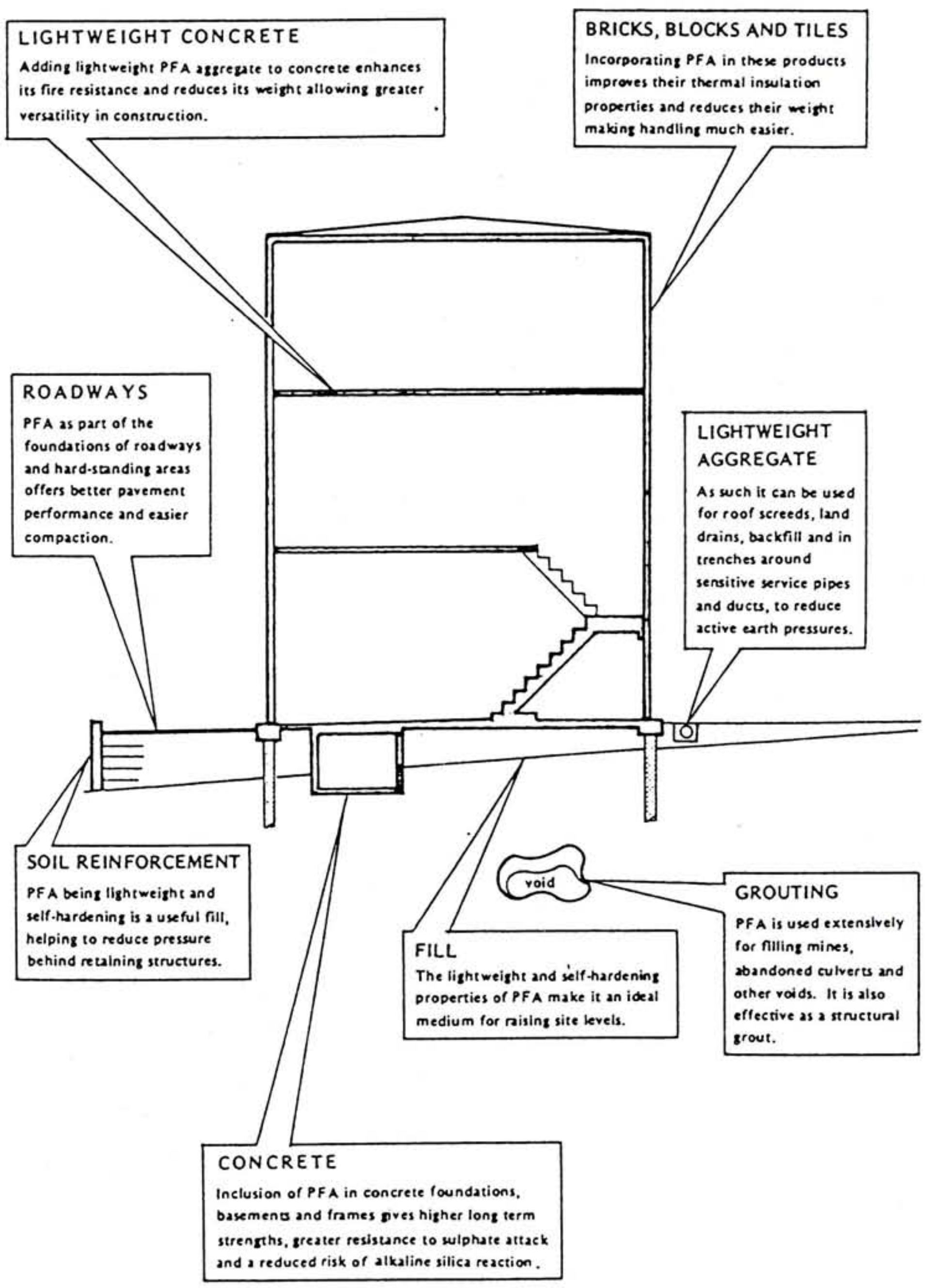

Fig. 1.2 Typical industrial uses of fly ash (HEC, 1988).

Fly ash is commonly disposed of in either settling lagoons or landfills. Settling lagoons are constructed for receiving ash in slurry form (the ash is mixed with freshwater or seawater to form a slurry and piped to the settling lagoon usually near the thermal power plant). After the ash particles have settled out, the overlying water is either discharged to receiving streams/sea or pumped back to the power station for reuse. The ash in lagoon can be temporarily stored until final removal for utilization or disposal elsewhere, or revegetated to reduce visual impact and provide a source of amenity land. For dry disposal of fly ash to landfill, a layer of soil is usually covered to the ash surface for the establishment of vegetation (Weinstein *et al.*, 1989). Apart from direct disposal of fly ash in settling lagoons or landfills, fly ash could also be co-disposed of with domestic sludge, which not only reduces the moisture of the sludge but also absorbs the heavy metals present in the leachate (Cossu *et al.*, 1991).

1.2 **Problems Associated with the Revegetation of Fly Ash**

Vegetation plays an important role on the environmental quality of ecosystems including fly ash lagoons. It stabilizes the ash against wind and water erosion, and provides a habitat for wildlife (Hodgson and Townsend, 1973; Hodgson and Buckley, 1975). Landscape quality can also be improved visually by plants. However, natural revegetation (conlonization of plants) of fly ash lagoon is slow. It took 40 to 50 years for dry ash spoil in England to resemble a normal soil (Shaw, 1992). As weathering proceeded, plant species richness and diversity increased. Phytotoxic symptoms are shown on some plants growing on fly ash. Probably physical, chemical and/or biological conditions in the ash are deleterious to plant survival and growth.

1.2.1 **Physical problems**

Physical characteristics of fly ash can inhibit successful vegetation establishment. Due to the pozzolanic properties of fly ash, which cement particles when wetted in the presence of liming material ($CaSO_4$) in the fly ash, compacted layers are formed which reduce aeration, water infiltration and root penetration (Hodgson and Townsend, 1973; Bradshaw and Chadwick, 1980). Lack of humus colloids makes structure of ash poor.

1.2.2 **Nutrient problems**

Some essential plant nutrients, particularly N, are deficient in fly ash. N is lacking in fly ash since most of the N is volatilized during coal combustion (Adraino *et al.*, 1980). P in fly ash is high (400-800 μg/g) (Page *et al.*, 1979) but it is not in a readily available form to plants probably due to complexation with ash Al and Fe (Townsend and Hodgson, 1973; Bradshaw and Chadwick, 1980). Ca, Mg, K, Na and other micro-nutrients are sufficient.

1.2.3 **Toxicity problems**

The most significant factors limiting vegetation establishment on ash deposits are the excessive concentrations of soluble salts and B (Carlson and Adriano, 1993). Soluble salt content of fly ash can result in electrical conductivity values larger than 4 mS/cm, at which level growth is adversely affected (Townsend and Gillham, 1975). B content of ash can exceed 250 μg/g which is above the level of 30 μg/g considered highly toxic to plants (Hodgson and Townsend, 1973; Hodgson and Buckley, 1975). High pH can also inhibit plant growth on ash, causing deficiencies of essential nutrients like P and essential trace elements such as Cu, Fe, Mn and Zn. Alkalinity of ash can, on the other hand, increase accumulation of some non-essential trace elements such as As, Se and V (Page *et al.*, 1979; Adriano *et al.*, 1980).

1.2.4 **Biological problems**

Fresh fly ash is microbiologically sterile when deposited. Invasion of microbes to ash starts when exposed to air and water. Although the microbial population and diversity generally increase as ash weathers and nutrients accumulate, the low content of organic matter seems to be a limiting factor for microbial populations (Klubek *et al.*, 1992). Development of a vigorous microbial community can increase the suitability of the ash as a substrate for plant growth (Rippon and Wood, 1975).

1.3 **Ecological Considerations on Wasteland Reclamation**

1.3.1 **Ecological basis**

Where land has been destroyed or changed by man-made activities like mining and waste disposal like disposal of fly ash, only skeletal materials are left, which will develop into an ecosystem on which soil can be formed with plant and animal colonization. Actually, this process of development is an ecological process called 'primary succession' which can be quantified in two dimensions which are structure (species diversity & physical and biological complexity) and function (productivity and nutrient cycling) (Bradshaw, 1984) (Fig. 1.3). When ecosystems are degraded by an operation, there is a reduction of both dimensions. It may recover slowly by natural succession or degrade further. If reclamation is actively carried out, three aims are possible. The first is restoration, in which an attempt is made to put back exactly what was there prior to the disturbance. Rehabilitation, only a partial return, is the second. The third possibility is replacement which implies ending up in some new state in which either structure or function is different from the original. There are many cases where restoration is either so difficult or expensive as to be impracticable while replacement should be the easiest to carry out since all the subtle characteristics of the original ecosystem are not required.

The degraded ecosystem may recover slowly by natural primary succession. The problem with leaving restoration to natural processes is that they take time which is measured in decades or centuries (Table 1.1). Redevelopment of advanced communities may take a millennium or more. Woodland may not appear even after 100 years on some colliery spoils in England (Hall, 1957), and also on lime wastes from the Leblanc process (Bradshaw, 1983). Except for speed, natural succession is a reliable process for land reclamation. Thus, it is important to understand the factors limiting succession at each point of its progress (Bradshaw, 1987). Once the specific problems are identified, the long time scale of succession can be overcome by artificial interventions which are most successful if we use or mimic natural processes (Dobson *et al.*, 1997).

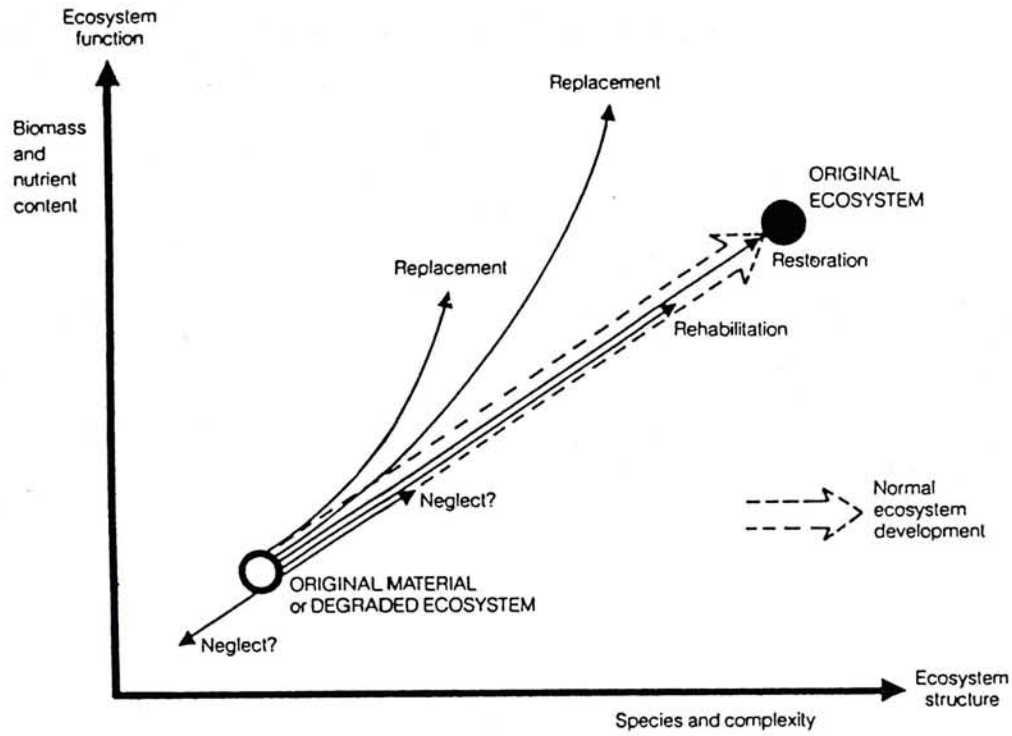

Fig. 1.3 A diagrammatic representation of the natural development of ecosystems and the different alternatives available in reclamation (Bradshaw, 1987).

Table 1.1 Processes involved in ecosystem development on degraded land (with approximate periods of time over which process is likely to be important): the biological processes are those most important in enabling plant growth to occur (Bradshaw, 1997).

Biological processes		Pedological processes	
Time (yrs)	Process	Time (yrs)	Process
1-50	1. Immigration of appropriate plant species	1-1000	1. Accumulation of fine material by rock
1-50	2. Establishment of appropriate plant species		
1-10	3. Accumulation of fine mineral materials	1-1000	2. Decomposition of soil minerals by weathering
1-100	4. Accumulation of nutrients by plants from soil minerals	1-100	3. Improvements of soil available water capacity
1-100	5. Accumulation of nitrogen by biological fixation and from atmospheric inputs	1-1000	4. Release of mineral nutrients from soil minerals
1-20	6. Immigration of soil flora and fauna supported by accumulating organic matter		
1-20	7. Changes in soil structure and organic matter turnover due to plant, soil micro-organism and animal activities		
1-20	8. Improvement in soil water holding capacity due to changes in soil structure		
10-1000	9. Reduction in toxicities due to accumulation of organic matter	10-10000	5. Leaching of mobile materials from suface to lower layers
		10-10000	6. Formation of distinctive horizons in the soil profile

1.3.2 **Problems of ecosystem development and its treatment**

There is obviously a great diversity of mining activity, producing mining materials of different characteristics (Table 1.2). These starting materials are usually extremely skeletal on wastelands. Their properties determine how ecosystem can develop naturally and what treatments are necessary to assist their development. Although there are many kinds of starting materials, there are characteristics and problems in common which can be grouped into four aspects, which are physical, nutrients, toxicity and plants and animals. In many sites, immediate replacement or the use of topsoil is not possible and economical. The quality of the so-called 'topsoil' is sometimes questionable. Usually, the original skeletal materials must be treated directly to achieve reclamation. These limiting factors can be treated separately by a wide variety of practicable methods (Gemmell, 1977; Schaller and Sutton, 1978; Bradshaw and Chadwick, 1980). The range of treatments commonly used is summarized in Table 1.3.

Physical factors

The major physical problem is usually compaction. This can be easily to relieved by ripping and cultivation. In situations where material is too loose, organic matter can be incorporated. Excessive wetness can always be relieved by drainage. In the long term, increase in organic matter content and reduction in bulk density due to the cumulative effects of plants and animals will itself improve the overall physical property.

Table 1.2 The range of factors hostile to plant growth likely to occur in different types of degraded land (Bradshaw and Chadwick, 1980).

	Physical problems				Chemical problems				
Materials	Texture & structure	Stability	Water supply	Surface temp.	Nitrogen	Other nutrients	pH*	Toxic materials	Salinity
Colliery spoil	---	---/o	-/o	o/+++	---	---	---/o	o	o/++
Strip mining	---/o	---/o	--/o	o/+++	---	---/o	---/o	o	o/++
Fly ash	--/o	-/o	o	o	---	---	+/+++	++	o/++
Oil shale	--	---/o	--	o/++	---	--/o	--/o	o	o/+
Iron ore	---/o	--/o	-/o	o	---	--	o	o	o
Bauxite	o	o	o	o	-/o	-/o	o	o	o
Heavy metals	---	---/o	--/o	o	---	---	---/+	+++/+	o/+++
Gold wastes	---	---	-	o	---	---	---/-	o/++	o
Kaolin wastes	---/-	--	--	o	---	---	-	o	o
Acid rocks	---	o	--	o	---	--	-	o	o
Calcareous rk	---	o	--	o	---	---	+	o	o
Sand/gravel	-/o	o	--/++	o	--/o	-/o	-/o	o	o
Coastal sand	--/o	---/o	--/o	-/o	---/o	--/o	o	o	o/+
Urban land	---/o	o	O	o	---/o	o	o	o/++	o
Roadsides	---/o	---	--/o	--/o	---/o	--/o	o	o	o
Ski runs	---	o	--	--	---	-/o	o	o	o

Note: Deficiency: --- severe, - slight adequate: o excess: + slight, +++ severe (*for pH: - low, + high)
actual score can vary between limits shown owing to site conditions and history of disturbance

Table 1.3 Underlying problems of derelict land and their treatment (Bradshaw, 1989).

Problem		Immediate treatment	Long-term treatment
Physical			
Structure	Too compact	Rip or scarify	Vegetation
	Too open	Compact or cover with fine material	Vegetation
Stability	Unstable	Stabilizer mulch	Regrade or vegetation
Moisture	Too wet	Drain	Drain
	Too dry	Organic mulch	Vegetation
Nutrition			
Macronutrients	Nitrogen	Fertilizer	Legume
	Others	Fertilizer + lime	Fertilizer + lime
Micronutrients		Fertilizer	-
Toxicity			
pH	Too high	Pyritic waste or organic matter	Weathering
	Too low	lime	Lime
Heavy metals	Too high	Organic mulch or metal-tolerant cultivar	Inert covering or metal-tolerant cultivar
Salinity	Too high	Weathering or irrigate	Tolerant species or cultivar
Plants and animals			
Wild plants	Absent or slow colonization	Collect seed and sow, or spread soil containing propagules, or plant	Ensure appropriate conditions
Cultivated plants	Absent	Sow normally or hydraulically	Appropriate aftercare
Animals	Slow colonization	Introduce appropriate animals	Ensure appropriate habitat

Nutrients

Deficiency of major nutrients is common. Immediate and effective remedy is application of fertilizer. However, growth usually decreases rapidly after treatment which is usually due to the reappearance of N deficiency. The supply of N to plants is by mineralization of the organic pool in the soil. This pool must be at least 1000 kg N ha^{-1} in temperate regions (Bradshaw, 1983). It seems not practical to accumulate this by the use of fertilizers. One possibility of N replenishment is through the addition of organic materials such as sewage sludge. The use of legumes and other N-fixing species which can accumulate at least 100 kg N ha^{-1} $year^{-1}$ (Dancer *et al.*, 1977) in an easily mineralizable form is another simple and cheap method. But there is a need to find species tolerant of difficult conditions (Jefferies *et al.*, 1981). Other nutrients like P and K may be in short supply in some materials. P may be complexed to waste materials, making it unavailable. Thus, it is important to carry out a proper soil analysis on the materials before reclamation is attempted to ensure adequate nutrients are provided as suggested by a systematic approach (Fig. 1.4). Further analyses should be made later to check whether any deficiencies reappear.

Toxicity

A common problem, particularly in coal mine wastes, is low pH, usually due to the oxidation of iron sulphide to give sulphuric acid. A simple treatment is to apply lime to neutralize the acid. For alkaline waste, application of pyritic waste or organic matter is possible. Heavy metal problems could be overcome with heavy applications of organic matter but the effect is only temporary (Goodman *et al.*,

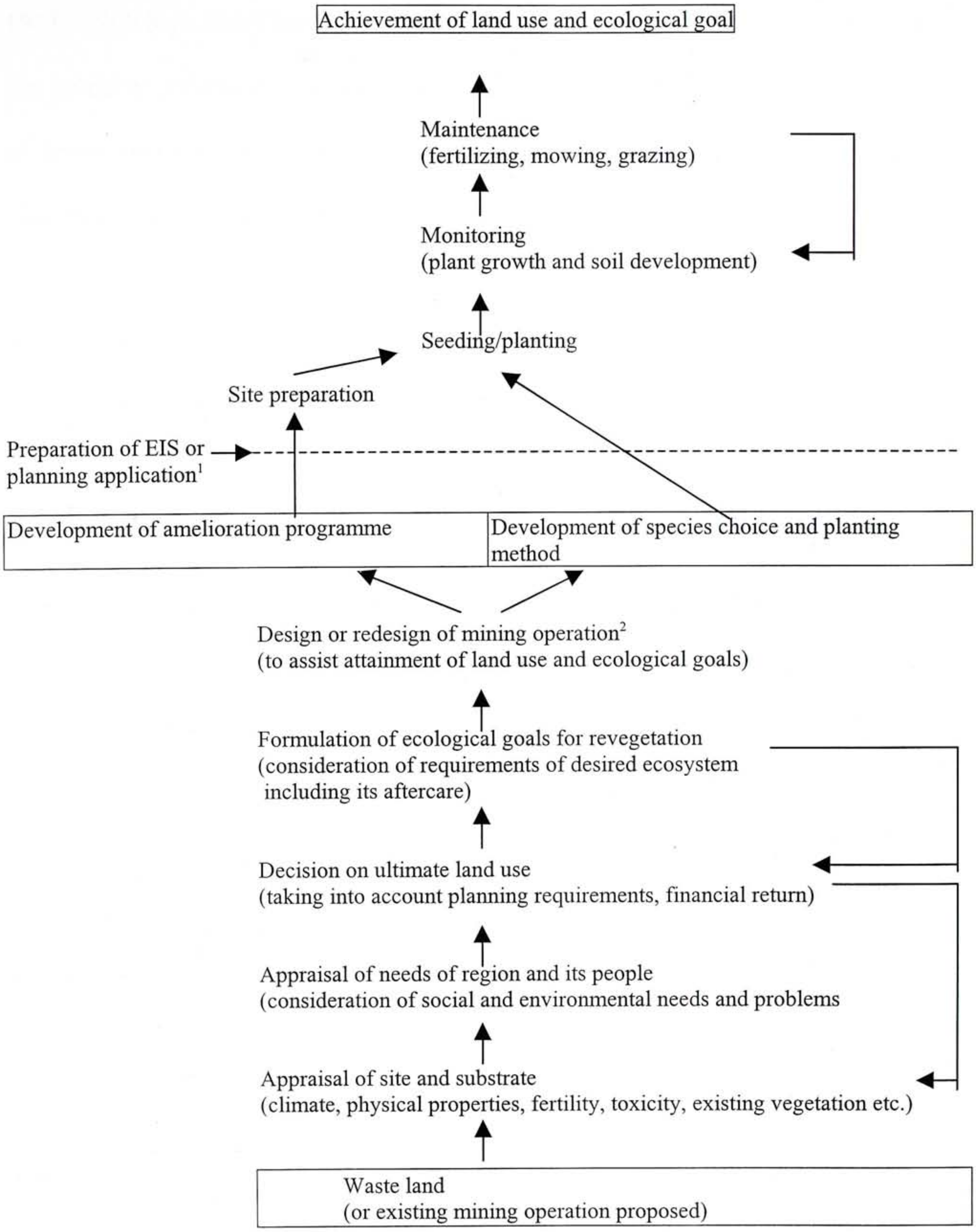

Fig. 1.4 The steps that need to be taken for the development of appropriate endpoints, and their subsequent achievement, in the reclamation of waste land (Modified from Bradshaw and Chadwick, 1980).

[1] will apply only to new developments

[2] will not apply to existing waste land

1973). With high metal levels, metal tolerant populations can be used and the effective can be enhanced by adequate nutrient supply (Smith and Bradshaw, 1979). If control of heavy metal or salt movement is required, it is necessary to provide an inert covering over the waste materials.

Plants and soil organisms

The establishment of species by natural processes tends to be slow and stochastic, depending on the source of propagules available in the vicinity and their dispersal ability. If the nearest source of appropriate immigrants is at a distance, colonization will be limited to those species with means of long distance dispersal, usually with small seeds (Ash *et al.*, 1994). Thus, introduction of appropriate species is necessary and important. This is particularly true for leguminous and other nitrogen-fixing species, which tend to have large seeds in facilitating ecosystem development. Trees are particularly sensitive to soil physical conditions but these can often be overcome by planting into pockets of suitable material which cannot only provide a physical isolation but also the necessary micro-organisms for better growth.

Soil organisms, including micro-organisms and soil fauna, help in soil decomposition processes, physical conditions and nutrient uptake. Toxicity of soil can reduce soil organism numbers and activity unless the situation is improved. Many soil fauna will colonize without assistance if the soil chemical conditions are appropriate except earthworms which have little mobility (Bradshaw, 1983).

The endpoint in all reclamation must be a self-sustaining ecosystem. The creation of such a system requires that all the underlying problems of the original site are overcome at the outset, whether these are physical, nutritional or toxicity. Otherwise, these problems will reappear.

1.4 **Objectives of the Present Study**

In Hong Kong, about one million tonnes of coal ash are produced every year by two electric power plants located in Castle Peak (Tuen Mun) and Lamma Island separately (EPD, 1993; Li, 1993; Premchitt and Evans, 1993). Apart from the ash consumed for industrial uses in various projects (Table 1.4), surplus fly ash, produced from the Castle Peak coal-fired power station, was disposed of by the lagooning method (CLP & BCL, 1990); mixing the ash with seawater and pumping the ash slurry from the power plant to a fly ash lagoon at Tsang Tsui (Grid Reference: 831 500N, 810 000E) which is about 6 kilometers away from the station (Fig. 1.5). The lagoon has an estimated total capacity of 7.5 million m^3 and occupies an area of nearly 60 hectares in the form of three adjoining sites, designated West, Middle and East (Fig. 1.6). The first delivery of ash commenced on 5 March 1987. The west lagoon (about 13 hectares) was filled completely in 1988; the middle one (about 23 hectares) in 1992 and the east one (about 16 hectares) in 1994. An embankment was built on the west lagoon afterwards and additional ash was delivered on to it. The surface of the lagoon was exposed and unshaded. A few plant species were observed growing on the ash but the colonization was slow.

Table 1.4 Summary of recent projects using PFA from China Light and Power Co. Ltd. (Ho and Chen, 1996).

Project	Quantity	Use of PFA
Tuen Mun New Town Area 2A Public Dump	44000 m^3	Fresh PFA disposal in a public dump on land
Tuen Mun New Town Area 2A Roads D7 and LD6	35000 m^3	Site formation and road embankment.
Tuen Mun New Town Area 7 Roads D6 and LD3 West	110000 m^3	Site formation and road embankment.
Tuen Mun New Town Area 16S Reclamation Areas 14 and 16S	50000 m^3	Above water reclamation.
Eastern Harbour Crossing	15000 m^3	Marine reclamation.
Siu Lang Shui Ash Disposal	320000 m^3	PFA landfill project.
Tsang Tsui Ash Lagoons	1500000 m^3	Storage lagoons.
Tuen Mun Area 47S Reclamation	50000 m^3	Reclamation of marsh.
Urmston Road Outfall	250000 m^3	Marine reclamation.
New Territories (6 projects)	230000 m^3	Reclamation of marsh and fish pond areas.

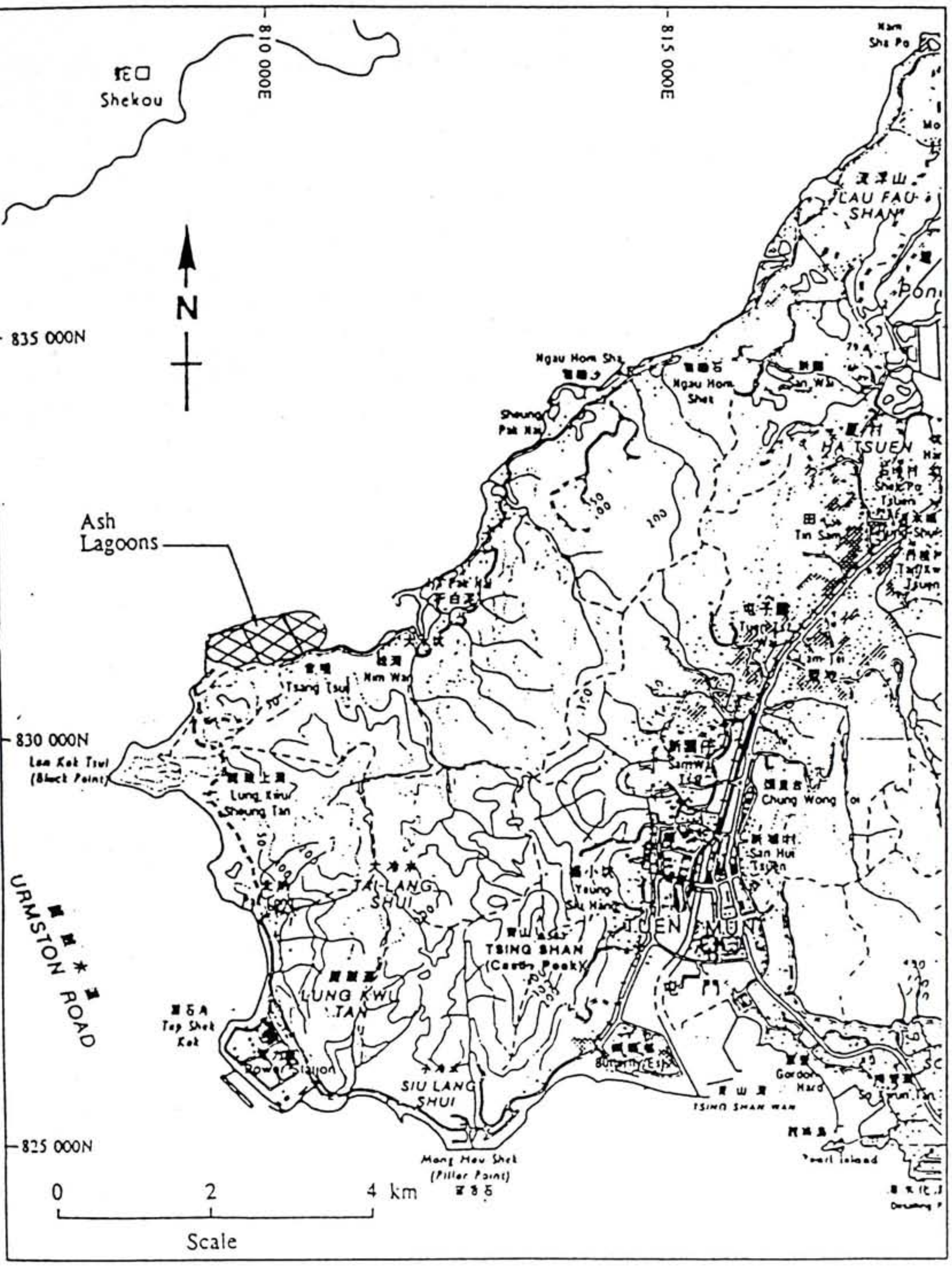

Fig. 1.5 Location of Tsang Tsui ash lagoons and the Castle Peak power station.

Plate 1.1 Aerial picture of Tsang Tsui ash lagoons (30th Aug. 1995).

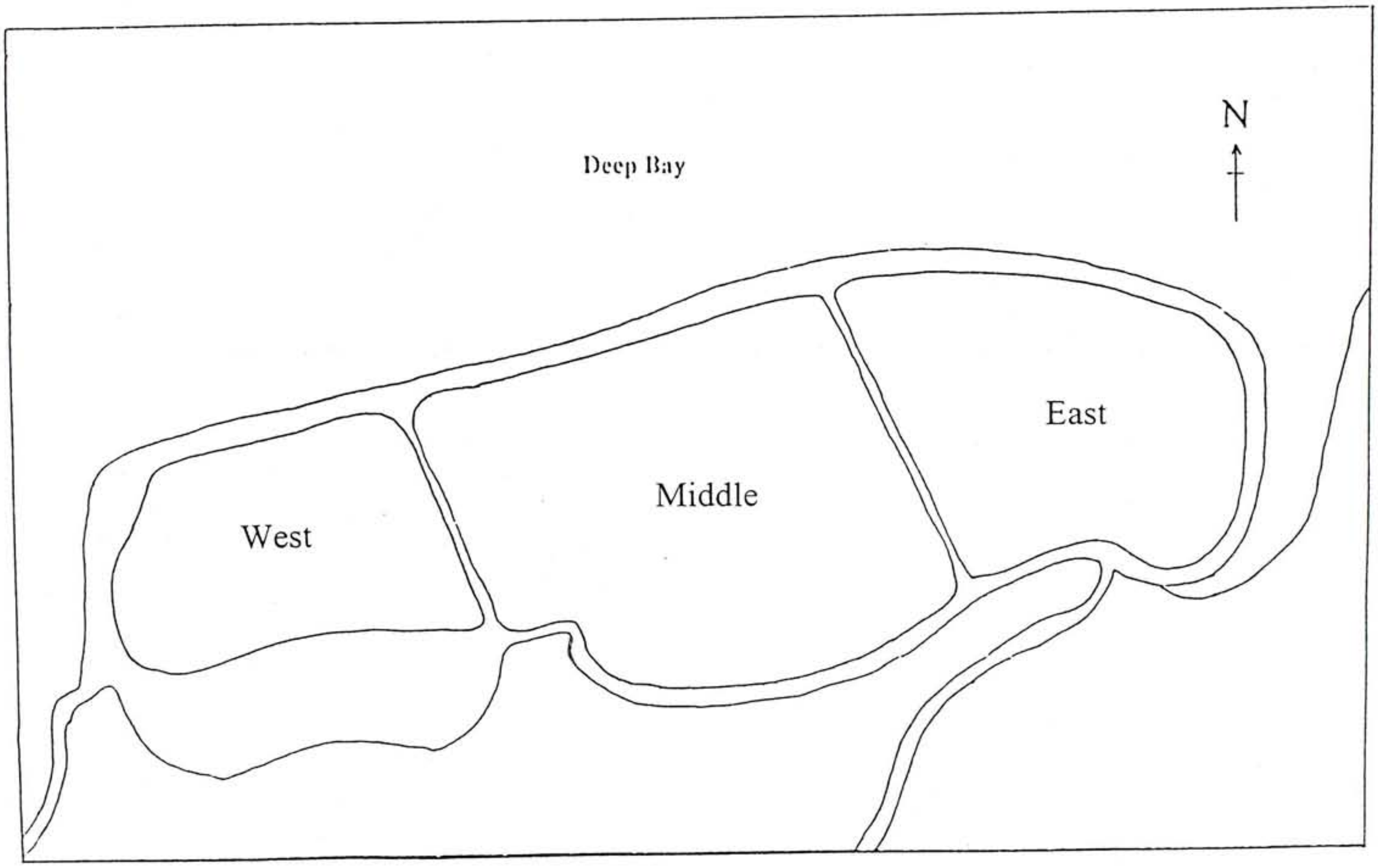

Fig. 1.6 Fly ash lagoon at Tsang Tsui. The three adjoining units from left to right are the west lagoon (13 ha), middle lagoon (23 ha) and east lagoon (16 ha) with an estimated total capacity of 7 million m^3.

Because of the variation of fly ash properties and their effects on plant growth, the physical and chemical characteristics of fly ash from disposal lagoons were determined so as to obtain the physical, nutrient and potential toxicities status of the ash. In Chapter 2, physical and chemical characterization of lagooned fly ash were performed by randomly sampling on the middle fly ash lagoon. A raw fly ash and a garden soil sample were also included for comparison. Not only the variation of fly ash properties on the lagoon surface, but also the vertical distributions of selected edaphological properties of lagooned fly ash were determined to see any trend of particular characteristic. The vegetation composition on the ash lagoon was also studied to obtain some information on the properties of the lagooned fly ash.

Selecting of plant species which are adapted or tolerant to the conditions on the ash lagoon would be a simple and effective way of revegetation. In Chapter 3, a greenhouse pot trial was conducted to select grass and tree species which could grow directly on the lagooned ash. Another pot trial was conducted using *Lolium perenne* as the test plant to determine the potential limiting factor(s) in lagooned ash (phytotoxicity, plant nutrient deficiency and poor physical condition). The plant nutrient deficiency of ash was further investigated so as to find out which element(s) (N, P and/or K) is/are the most limiting.

The most probable plant growth limiting factor of lagooned fly ash was due to the toxicities of soluble salts and B. In order to study the feasibility of removing them from lagooned ash, a column leaching study was conducted (Chapter 4). The vertical distributions of salts and B in columns were determined as related to different amounts of leaching water. The effect of leaching on plant growth was also determined.

Since deficiencies in plant growing nutrients of lagooned fly ash were other limitations to plant growth, the effect of amending lagooned fly ash by organic wastes was conducted by a pot trial reported in Chapter 5. Four organic wastes (sewage sludge, pig manure compost, horse manure compost and spent mushroom compost) were added to fly ash at two application rates (50 and 100 tonnes/ha). The effects of waste amendments on plant growth and elemental uptake from ash were determined.

By conducting the studies listed above on lagooned fly ash using an ecological approach for reclamation, it was hoped that the plant growth limiting factor(s) could be identified. This allows the succession processes on the lagoon to be accelerated by appropriate treatments (including the introduction of adapted or adaptable plant species, removal of toxicity by leaching and application of organic amendments) so that practical suggestions could be provided for the revegetation of the lagoon.

Chapter 2 **EDAPHOLOGICAL CHARACTERISTICS OF FLY ASH AND VEGETATION COMPOSITION ON FLY ASH LAGOONS**

2.1 **INTRODUCTION**

Fly ash usually amounts to more than 70% of the total amount of residues produced in the power plants. At present, only 10 - 20% of the total coal residues produced all over the world is being commercially utilized (Sikka and Kansal, 1994). The rest is disposed of in landfills or lagoons. The usual method is transport as a slurry to a settling basin with removal of water by surface drainage (Adriano *et al.*, 1980; Alberts *et al.*, 1985).

The chemical properties of fly ash are dependent on the coal source, lagooning process and the age (Fulekar and Dave, 1986). Generally fly ash is deficient in plant nutrients especially N and P. The relatively high alkalinity and trace element content can retard the growth of plants.

The slow rate of natural colonization and the limited number of species on ash lagoons during the first few years reflect the adverse plant growth conditions in ash (Hodgson and Townsend, 1973). The first colonizer on ash deposits in Britain is the moss *Funaria hygrometrica*. *Atriplex hastata* was observed almost simultaneously. As weathering commences, higher plant species appear. Three woody and thirty two herbaceous plant species have been reported from alkaline ash pits in Tennessee (Gonsonlin, 1975). Woody species like *Ulex europaeus*, *Betula verrucosa* and *Salix* sp. appeared on ash residues in Britain (Hodgson and Townsend, 1973). However, all tree species established on ash deposits showed some abnormalities such as reduced vigour, chlorosis and necrosis indicating nutrient deficiencies and/or the presence of toxicities.

Fly ash properties vary. Sampling of lagooned ashes for physical and chemical analysis can provide site-specific information which is important to characterize their specific properties so that the underlying plant growth limiting factor(s) can be identified. Moreover, wastelands often support extremely distinctive vegetation (Gemmell, 1977). Some plant species are abundant on the wastes but are rare or absent in the natural habitats of the area. Some of the sites are sufficiently attractive and valuable as ecological refuges to be preserved as they are (Bradshaw, 1979). Sampling the vegetation on a fly ash lagoon could record some interesting plant species. Also, the vegetation composition on a lagoon can provide information on the properties of lagooned ash and the direction for plant selecting trials. In the present study, edaphological properties of lagooned fly ash were determined and compared with those of raw fly ash and a garden soil. The vertical distributions of selected edaphological parameters were determined. The natural vegetation composition on the fly ash lagoon located at Tsang Tsui was also studied.

2.2 MATERIALS AND METHODS

2.2.1 Site description

The fly ash lagoon was constructed on the foreshore at Tsang Tsui, 6 kilometers away from the Castle Peak power station (see Fig. 1.5). The lagoon has an estimated total capacity of 7.5 million m^3 and occupies an area of nearly 60 hectares in the form of three adjoining sites, designated west (about 13 hectares), middle (about 23 hectares) and east (about 16 hectares) (see Fig.1.6). All of the three lagoons has already been filled in turn, from West to East. The west lagoon was filled completely in 1988; the middle one in 1992 and the east one in 1994. The surface of the lagoon was grey in colour. It was exposed and unshaded. Average annual rainfall in Hong Kong is about 2300 mm for the last ten years (Royal Observatory, 1996). The rainy season is between June to September. Flooding was usually observed after heavy raining especially during the rainy season. No fertilizer was applied to the lagoon and vegetation on the lagoon was patchy and concentrated on the periphery of lagoons. Due to the extent of disturbance of the west lagoon coupled with the potential collapse of the recently filled east lagoon, the middle lagoon was selected for the present study.

2.2.2 **Collection of fly ash and soil samples**

In April 1995, fifteen ash samples were collected from 0-15 cm depth along a 'W' shape transect line on the middle lagoon (Rowell, 1994). In addition, seven sampling points were selected randomly from the lagoon where ash was collected along a vertical profile at depths 0-2.5 cm, 2.5-7.5 cm, 7.5-12.5 cm, 17.5-22.5 cm, 37.5-42.5 cm and 57.5-62.5 cm. Raw fly ash and a garden soil were also obtained in May 1995 for comparison of the chemical composition. The former was collected from the electrostatic precipitators in the Castle Peak power station and the latter from a nursery in the campus of the Chinese University of Hong Kong. All the materials were returned to the laboratory for soil analysis.

2.2.3 **Physical analysis**

Texture of lagooned fly ash, raw fly ash and garden soil was assessed using the Bouyoucos hydrometer method (Day, 1965) after pretreatment of the ashes to remove soluble salts. Bulk density, particle density, porosity and saturation capacity of the lagooned fly ash were also determined (Rowell, 1994). Penetration resistance of the surface of fly ash from the middle lagoon was measured *in situ* by a cone penetrometer with probe diameter of 30 mm with a 90° angle (Bradford, 1986). The penetration resistance (Q_p) was calculated from the equation:

$$Q_p = 4F/\pi d^2$$

where d was the diameter of cone and F was the force required to penetrate the soil.

2.2.4 **Chemical analysis**

The lagooned fly ash, raw fly ash and garden soil were air dried for one week. They were then sieved through a 2-mm mesh sieve, bulked and kept in polyethylene bags prior to the determination of their various chemical properties following the procedures as described by Allen *et al.* (1989). The materials were analyzed for pH (pH meter, sample : 0.01 M $CaCl_2$ = 1:2.5 (w:v)), electrical conductivity (conductivity meter, in saturation extract); organic carbon (Walkley and Black, 1934); total and extractable nitrogen (colorimetric method with a Lachat QuickChem AE Automated Ion Analyzer after salicylic acid modification of Kjeldahl digestion and extraction with 1 M potassium chloride, respectively); total and extractable phosphorus (molybdenum blue method with Lachat QuickChem AE Automated Ion Analyzer after salicylic acid modification of Kjeldahl digestion and extraction with 0.5 M sodium bicarbonate at pH 8.5, respectively); total and extractable potassium, calcium, magnesium, sodium, copper, zinc, lead and cadmium (atomic absorption spectrophotometry after nitric acid-sulphuric acid (5:1) digestion and 1 M neutral ammonium acetate extraction, respectively; and total and hot water extractable boron (inductively coupled plasma-atomic emission spectrometry (ICP-AES) after nitric acid-sulphuric acid (5:1) digestion and azomethine-H method with Lachat QuickChem AE Automated Ion Analyzer, respectively).

2.2.5 **Vegetation analysis**

At the seaward side of the middle lagoon, an area of 30 m × 30 m was selected for vegetation analysis (since most of the vegetation was located at the periphery of the lagoon and was barely found in the centre.) The area was subdivided into 100 grids (9 m^2 each), and three (1m × 1m) quadrats were laid randomly within the 9 m^2 grid. A total of 300 quadrats was selected from the 100 grids in such a stratified random manner. From each quadrat, all species of vascular plants were recorded, and their percentage cover and density were estimated visually (Plate 2.1). The importance value (as the summation of relative density, relative dominance and relative frequency) for each species was calculated (Kent and Coker, 1992).

2.2.6 **Statistical analysis**

Untransformed data of the vertical profiles of the lagooned fly ash were subjected to one way analysis of variance (ANOVA) at the 0.05 significance level to test of the difference among different depths. Least significant difference (LSD) for the means was calculated where necessary at the 0.05 significance level. All statistical analyse were performed by means of SPSS for Windows Release 6.0 (SPSS, 1989).

2.3 RESULTS AND DISCUSSION

2.3.1 Physical properties

The particle size distribution of the lagooned fly ash contained 46.4% sand (0.02-2 mm), 44.2% silt (0.002-0.02 mm), and 9.4% clay (<0.002 mm) while the raw fly ash had 19.2% sand, 36.1% silt and 44.7% clay (Table 2.1). Lagooned fly ash therefore had a relatively larger fraction of sand-sized and silt-sized particles than raw fly ash. According to International Soil Science Society (ISSS), the soil texture of the lagooned and raw ash resembles that of loam and clay soil respectively (Allen, 1989). Using the same particle fractionation system, the garden soil used was classified as a sandy loam.

Storage and handling of the ash are factors affecting the physical properties of fly ash (Van Hook, 1979; Adriano *et al.*, 1980). The difference in texture between the ashes might be the result of redistribution of fly ash during settlement

Table 2.1 Physical properties of lagooned fly ash, raw fly ash and garden soil.

	Lagooned fly ash	Raw fly ash	Garden soil
Texture: sand (%)	46.4*	19.2	68.5
silt (%)	44.2	36.1	16.2
clay (%)	9.4	44.7	15.3
Textural class	loam	clay	sandy loam
Bulk density (g/cm^3)	0.88 (0.05)**	nt[@]	nt
Particle density (g/cm^3)	1.88 (0.05)	nt	nt
Porosity (%)	88 (1)	nt	nt
Saturation capacity (%)	56 (6)	nt	nt
Penetration resistance (KPa)	985 (465)	nt	nt

* Values are means of 15 replicates for lagooned fly ash and 3 replicates for raw fly ash and garden soil.
**Standard deviation of mean is parenthesised.
[@]nt represents not tested.

process in the storage lagoon, making the clay-sized fraction of the surface (0-15 cm) lesser in amount. They might be washed away through the decantrate. Other factors which would affect the physical properties of fly ash include the composition of the parent coal, conditions during coal combustion, efficiency of emission control devices, climate and the weathering process of ash during storage (Adriano *et al.*, 1980).

The bulk density, porosity and saturation capacity of the lagooned fly ash were 0.88 g/cm^3, 88% and 56% respectively. Bulk density of British coal ashes ranged from 0.99 to 1.73 g/cm^3 (Townsend and Hodgson, 1973). Cope (1962) recorded the bulk density of fly ash as in the range 0.56 to 1.13 g/cm^3. Most soils have a bulk density between 0.8 g/cm^3 (an open soil with plentiful pore space) and 1.7 g/cm^3 (a compact soil that would affect root penetration) (Russell, 1977). Soil bulk density of more than 1.8 normally inhibits root growth completely (Ayerst, 1978). Based on these criteria, lagooned fly ash seems to be not very compact in terms of its bulk density. It could retain a good deal of space for water, air and heat transportation (as shown by its high porosity and saturation capacity) which are essential for plant growth. However, it is unclear whether the high water saturation capacity and porosity reflect a greater availability of water to plants since the amount of water that becomes available to plants depends on how strongly the water is held by the particles as well as the influence of soil structure, pore size, pore distribution and hydraulic conductivity. The increase in moisture does not necessary produce an increase in plant growth (Salter and Williams, 1967).

The particle density of lagooned fly ash was found to be 1.88 g/cm^3. Fly ash with a specific gravity of 2.1 to 2.6 has been reported (Adriano *et al.*, 1980). As compared to quartz (SiO_2, 2.65 g/cm^3) and mullite ($Al_6Si_2O_{13}$, 3.23 g/cm^3), which dominated the crystalline phase of the ashes (Aitken *et al.,* 1984), the particle density of lagooned fly ash was lower suggesting the presence of light weight and probably porous particles like cenosphere (hollow spherical particles) and plerospheres (large spheres containing smaller spheres) (Fisher *et al.*, 1976; Page *et al.*, 1979). The significance of the porous nature of some particles to the physical properties is in several ways. Firstly, it could contribute to the increase of the water holding capacity (saturation capacity) of fly ash (Chang *et al.*, 1977). In many other studies, fly ash is used as a soil amendment to increase the water retention capacity of coarse-textured soils (Salter and Williams, 1967; El-Mogazi *et al.*, 1988; Lisk and Weinstein, 1988; Ghodrati *et al.*, 1995). Secondly, the compactness of the lagooned ash in terms of bulk density would be underestimated if using the same criteria for soil. It means that lagooned fly ash might be, to a certain extent, compact although the bulk density is 0.88 g/cm^3 (which is classified as open for soil). Moreover, the associated disadvantage of low particle density is the potential for increased dust formation. In a wind tunnel test using open-ended trays of dry ash exposed to a non-turbulent air stream, the ashes are especially erodible, with an erosion threshold between 9-11 m/sec (32 to 40 km/hour) (Cope, 1962), indicating that these particles are easily airborne, causing a problem of wind erosion on ash lagoons. Although this problem can, to some extent, be reduced by spraying or capping of surfaces, considerable dust nuisance can arise if the surface cap is broken (Townsend and Hodgson, 1973).

The penetration resistance of lagooned fly ash was 985 KPa. According to Greacen (1969), the critical value of penetration resistance at which root elongation ceases is in the 800-1500 KPa range, depending on the soil and plant. A possible explanation for the hardness on the surface of ash lagoon is due to the pozzolanic reaction of fly ash, which cements particles when wetted in the presence of liming material ($CaSO_4$) in the fly ash (Townsend and Hodgson, 1973; Adriano *et al.*, 1980; Bradshaw and Chadwick, 1980) or is due to the formation of ettringite ($3CaO \cdot A_{12}O_3 \cdot CaSO_4 \cdot 31H_2O$) (Simons and Jeffrey, 1960). Other factors influencing penetration resistance are matric potential (water content), bulk density, soil compressibility, soil strength and soil structure (Taylor and Gardner, 1962). Root development in ash with a compact surface layer was found to be confined to the top 8 cm, with roots ramifying horizontally (Hodgson and Buckley, 1975). Although plant roots are flexible and can grow through zones of least resistance like root channels or develop horizontally, root elongation and water infiltration will be reduced, if not totally retarded, by the hard and compact layer of the lagoon as a whole (Hodgson and Townsend, 1973; Townsend and Hodgson, 1973; Hodgson and Buckley, 1975; Townsend and Gillham, 1975; Bradshaw and Chadwick, 1980; Bengough and Mullins, 1990).

An impeded root system may have reduced capacity to take up less mobile nutrients like phosphorus. Shierlaw and Alston (1984) found a significant negative correlation between shoot P content and levels of soil compaction. This is a direct consequence of the decrease in root growth, probably decrease in diffusion coefficient of P, due to high tortuosity (Nadian *et al.*, 1996) and decrease in total root length per plant colonized by VAM fungi which can enhance uptake by providing a larger absorbing surface and by overcoming problems which relate to the development of depletion zone, via translocation in external hyphae to the host plant root (Cooper and Tinker, 1978). Therefore, deep ploughing and organic amendments have been used to improve the ash physical conditions by disrupting the impeding layer during land reclamation (Hodgson and Townsend, 1973).

2.3.2 **Chemical properties**

The pH and electrical conductivity of lagooned fly ash was 8.3 and 120 mS/cm respectively (Table 2.2). As compared to the pH and electrical conductivity of raw fly ash, lagooned fly ash was less alkaline but substantially higher in soluble salt content. When compared to garden soil, both ashes were alkaline and had higher electrical conductivity.

The pH and electrical conductivity (a measure of soluble salt content) of fly ash depend largely on the coal source, lagooning processes and age of ash (Fulekar and Dave, 1986; Carlson and Adriano, 1993). High Ca/Mg and low S coal like lignite and sub-bituminous coal generally produces alkaline fly ash. The pH of some

Table 2.2 Chemical properties of lagooned fly ash, raw fly ash and garden soil.

	Lagooned fly ash			Raw fly ash			Garden soil		
pH	8.3*	±	0.3	12.4	±	0.1	6.4	±	0.1
EC (mS/cm)	120	±	20	13.9	±	1.0	1.24	±	0.10
Organic C (%)	0.27	±	0.05	0.05	±	0.04	4.21	±	0.12
N Total (%)	0.10	±	0.04	0.08	±	0.01	0.22	±	0.01
Ext NH_4^+-N (μg/g)	1.43	±	0.61	0.22	±	0.11	5.24	±	0.17
Ext NO_3^--N (μg/g)	2.02	±	1.76	0.14	±	0.13	29.2	±	0.2
P Total (%)	3.63	±	0.81	3.43	±	0.05	0.04	±	0.01
Ext PO_4^{3-}-P (μg/g)	64.5	±	41.2	294	±	13	110	±	4
K Total (%)	0.15	±	0.04	0.10	±	0.02	0.37	±	0.03
Ext (μg/g)	634	±	210	9.27	±	3.45	105	±	4
Na Total (%)	2.27	±	0.27	0.04	±	0.01	0.03	±	0.01
Ext (μg/g)	12900	±	600	55.0	±	12.0	36.8	±	13.7
Ca Total (%)	2.06	±	0.72	2.61	±	0.06	0.46	±	0.00
Ext (μg/g)	11900	±	4400	9500	±	880	3340	±	1920
Mg Total (%)	0.63	±	0.10	0.45	±	0.08	0.01	±	0.00
Ext (μg/g)	843	±	136	67.9	±	3.3	50.0	±	5.0
B Total (μg/g)	190	±	105	285	±	13	51.6	±	8.1
Ext (μg/g)	17.5	±	16.8	42.8	±	1.3	0.44	±	0.63
Cu Total (μg/g)	34.0	±	5.8	32.6	±	2.8	9.93	±	0.88
Ext (μg/g)		nd		0.64	±	0.10	0.12	±	0.12
Zn Total (μg/g)	66.5	±	21.2	85.2	±	47.6	115	±	18
Ext (μg/g)		nd			nd		0.42	±	0.30
Pb Total (μg/g)		nd		80.3	±	14.9		nd	
Ext (μg/g)		nd			nd			nd	
Cd Total (μg/g)		nd			nd			nd	
Ext (μg/g)		nd			nd			nd	

* Values are means of 15 replicates ± standard deviation for lagooned fly ash and 3 replicates ± standard deviation for raw fly ash and garden soil.
nd represents not detectable.

alkaline ashes can exceed 12 (Adriano *et al.*, 1980; Bradshaw and Chadwick, 1980). This alkalinity of fly ash was most likely due to the hydrolysis of oxide forms of Ca, Mg, Na and K (Elseewi *et al.*, 1980).

Lagooned fly ash showed a large difference in pH and electrical conductivity as compared to raw fly ash. When fly ash was subjected to weathering in a lagoon, significant changes in the chemical and mineralogical properties of fly ash occur. Chemical reactions determining ash weathering are not well understood but it is suggested that hydration and carbonation play important roles in transforming the primary minerals such as CaO and MgO in the fly ash into less reactive secondary mineralogical products. The reaction kinetics leading toward a chemical stabilization are probably controlled by the rate of CO_2 diffusion into the ash matrix. As a result, the pH and electrical conductivity of fly ash become stabilized with time (Page *et al.*, 1979; Adriano *et al.*, 1980; Adriano *et al.*, 1982).

However, only based on this explanation, it cannot account for the large increase in electrical conductivity of lagooned fly ash. Electrical conductivity of fly ash extracts, although not related precisely to percentage of soluble salts, gives an indication of total salt concentration (Elseewi *et al.*, 1980). In regions where rainfall exceeds evapotranspiration, salts leach from ash naturally. Electrical conductivity generally dropped below toxic levels (Townsend and Gillham, 1975). During the lagooning process, fly ash was mixed with seawater and pumped to Tsang Tsui ash lagoon by pipelines. The supernatant sea water, after settlement of the fly ash, was pumped back to the power station for marine disposal after dilution by cooling water from the power plant. Therefore, lagooned fly ash had been, in effect, subjected to a sea water extraction process. Soluble salts in sea water would aggravate the soluble salt concentration of the fly ash. As a result, the electrical conductivity of lagooned fly ash was higher than that of raw fly ash, which is contrary to the case when fly ash was transported by means of fresh water to disposal lagoons (Townsend and Gillham, 1975; Sikka and Kansal, 1994). Moreover, buffering capacity by the action of bicarbonate ion as well as other major cations and anions from seawater could additionally explain the reduced pH value of lagooned ash compared to raw ash.

High pH can be a factor limiting plant growth on ash lagoons. It can on the one hand cause deficiencies of essential nutrients such as P and essential trace element such as Cu, Fe, Mn and Zn, and on the other hand, alkaline ash can also cause increased accumulation of some nonessential trace elements such as As, Se, Cr, Mo and V, whose solubilities are pH-dependent (Townsend and Gillham, 1975; Page *et al.*, 1979; Adriano *et al.*, 1980). Gonsoulin (1975) indicated that substrate pH was one of the major factors controlling the woody species composition of abandoned ash basins in Tennessee. pH also probably was the dominant factor influencing tree growth on some ash basins (Carlson and Adriano, 1991). Weathering and natural leaching will reduce alkalinity but the pH usually stabilizes at a value above those found in productive soils. Complete neutralization of surface ash may involve the addition of huge amounts of strong acid which may not be practical and economical (Hodgson and Townsend, 1973). Although there may be indirect effects on plant growth by influencing the concentrations of phytotoxic ions in the aqueous phase (Collier and Greenwood, 1977), high pH seems not to be a primary toxicity factor.

High salts content is one of the most significant factors limiting vegetation establishment on ash deposits (Townsend and Gillham, 1975; El-Mogazi *et al.*, 1988; Brieger *et al.*, 1992). For most plants, growth is adversely affected at electrical conductivity values (measured in saturation extraction) $\geq$ 4 mS/cm (U.S. Salinity Laboratory Staff, 1954; Townsend and Gillham, 1975). Between 2 to 4 mS/cm, growth of sensitive plants could also be affected. Since electrical conductivity in both lagoon and raw fly ash greatly exceeded the critical value, inhibition of plant establishment and growth would result. Although some studies showed that weathering can reduce the salt content to a harmless level after 2 to 3 years of lagooning (Jones and Lewis, 1960; Townsend and Hodgson, 1973; Townsend and Gillham, 1975; Sikka and Kansal, 1994), it seems that a longer time is needed due to the addition of soluble salts from seawater during the sluicing process.

Organic C, total N, extractable ammonium and nitrate were low, but total P was higher in both lagooned and raw fly ash as compared to the garden soil (Table 2.2). Regarding metal contents, except in raw fly ash, no Pb or Cd was detected in ashes and soil. As in soil, only a portion of the total metal was present in extractable form. Extractable contents of Cu and Zn in lagooned fly ash and extractable Zn in raw fly ash were also below detection limits.

Fly ash contained little organic C and N because they had been volatilized during combustion (Hodgson and Townsend, 1973; Townsend and Hodgson, 1973). While there were generally higher concentrations of P in ashes than that of soil as shown in other studies (Page *et al.*, 1979; Townsend and Hodgson, 1973;), the P present is not in a form readily available to plants, presumably due to interactions with ash Al and Fe, in the case of highly alkaline ash, with Ca (Townsend and Hodgson, 1973; Bradshaw and Chadwick, 1980). Therefore, to ensure ecosystem production does not decline, successive fertilization using organic matter like sludge is necessary (Hodgson and Townsend, 1973; Townsend and Gillham, 1975; Bradshaw and Chadwick, 1980).

Accumulation of organic C and N was noticed in lagooned fly ash as compared to raw fly ash (Table 2.2). Organic matter and decomposer activity increased with the fly ash deposits age (Shaw, 1992). Comparison between unweathered and weathered fly ashes indicates that weathering significantly increases the organic C content (Khandkar *et al.*, 1993). The increase in organic C could be attributed to organic enrichment through air and water-borne organic materials, colonisation of blue green algae during flooding period and microbial activity during the course of natural weathering. Besides, vegetation invading the lagoon also contributes to organic input to the lagoon via litterfall and dieback. Significant increases in invertebrates population and diversity in vegetated fly ash than bare ash in the middle fly ash lagoon were also recorded (Law, 1997). Vegetation can also promote the colonization of soil animals which could enhance the litter decomposition process and hence nutrient recycling (Hutson, 1980).

Chemically, all naturally existing elements can be found in fly ash which is substantially enriched in trace metals compared with the parent coal (Klein *et al.*, 1975; Van Hook, 1979; Adriano, 1980). The increases in Ca, Na and Mg in lagooned ash are mainly due to enrichment from seawater which was used as the transport medium, leading to the high electrical conductivity. Considering 360 μg/g Ca, 120 μg/g Mg and 49 μg/g K as the critical limits (Chapman, 1960), these elements were present in fly ash in concentrations toxic to plant growth. The calculated exchangeable sodium percentage (ESP) of lagooned fly ash was approximately 61 which is considered to be saline-sodic and toxic to most plants. Although the effect of sodium on plants could be affected by many factors (like texture and clay mineralogy), ESP values above 9 are critical to most crops (Chapman, 1960).

The water solubilities of trace metals are profoundly influenced by the particle size and equilibrium pH of the fly ash suspension (Phung *et al.*, 1979; Elseewi *et al.*, 1980; Mishra and Shukla, 1986; Hollis *et al.*, 1988). The concentration of various elements in fly ash decreased with increasing particle size (Davison *et al.*, 1974; Klein *et al.*, 1975, Adriano *et al.*, 1980; Mishra and Shukla, 1986; Wadge *et al.*, 1986) which has been hypothesised to be a result of volatilisation of elements upon combustion, followed by surface condensation and deposition as the ambient temperature drops.

The higher total Zn and Pb contents in raw ash than lagooned ash (Table 2.2) might be due to its higher clay-sized fraction.

Solubility of trace elements is extremely low at high pH and the solubility increases as pH decreases (Phung *et al.*, 1979; Elseewi *et al.*, 1980; Mishra and Shukla, 1986). This could explain the low extractable metal (Cu, Zn, Pb and Cd) contents of lagooned and raw fly ash in the alkaline state. In a study on fly ash stockpiles, the actual amount of trace elements released from fly ash in natural waters (pH 7-8.5) depended not only on pH, but bonding between the element and the fly ash, its chemical form, the chemical and physico-chemical properties of the water, ion exchange, precipitation, and sorption/desorption (Phung *et al.*, 1979; Mattigod, 1990).

Of the constituents in fly ash, B has been considered as the element most likely candidate to cause phytotoxicity (Holliday *et al.*, 1958; Hodgson and Holliday, 1966; Hodgson and Townsend, 1973; Hodgson and Buckley, 1975). The total and extractable B content of the lagooned fly ash (190 μg/g and 17.5 μg/g respectively) were lower than that of raw fly ash (285 and 42.8 respectively) (Table 2.2). B concentrations of several hundred micrograms per gram have been reported (Dudas, 1981; James, 1982) with many fly ashes exceeding 1000 μg/g (Cox *et al.*, 1978; James, 1982). The range between deficiency and toxicity of B to plants is narrow (Adriano *et al.*, 1980; Keren and Bingham, 1985). Keren and Bingham (1985) suggested 3-5 μg/g B, below which phytotoxicity should not normally be a problem. Overall for plant growth, a level less than 4 μg/g B seems to be widely considered as non-toxic, 4-10 μg/g B slightly toxic, 11-20 μg/g B moderately toxic, 21-30 μg/g B toxic and > 30 μg/g B highly toxic (Hodgson and Townsend, 1973; Hodgson and Buckley, 1975). Based on this, lagooned fly ash and raw fly ash had levels of B considered to be toxic and highly toxic respectively. The difference would be mainly attributed to dissolution of B during the sluicing process of ash into lagoons as well as natural weathering during settlement.

B is a micronutrient required for the successful growth of higher plants, but confusion still exists in defining B limits for plant growth (Perkins and Vann, 1995). A variety of factors makes generalizations difficult. The predominant forms of B in fly ash are probably soluble borates and less soluble borosilicates (James, 1982). B toxicity is essentially long-term due to slow release of soluble B by hydrolysis of the borosilicates in the glassy phase of the ash (Hodgson and Townsend, 1973; Warren and Dudas, 1984). Alkaline conditions (like the case in fly ash) decrease B solubility, while neutral and acid reactions promote its solubility and release into solution (Phung *et al.*, 1979; Elseewi *et al.*, 1980; Keren and Bingham, 1985; Mishra and Shukla, 1986). Plant species may exhibit different degrees of B tolerances, and synergistic or antagonistic interactions exist with other soil elements (Keren and Bingham, 1985).

2.3.3 **Vertical ash profile**

The ash surface had a lower pH than the lower horizon (Fig. 2.1) while the vertical ash profiles of other measured edaphological parameters (Figs. 2.2 and 2.3) shared a common trend of accumulation on the ash surface (0-10 cm) and decrease with increasing depth. The N (including total N, ammonium-N and nitrate-N) and organic C contents were the highest on the surface 10 cm and then declined with depth. P (total and extractable) contents fluctuated but decreased along the ash profile. The electrical conductivity declined gradually from the surface (112 mS/cm) to nearly one half at the bottom (63.8 mS/cm). Extractable Na, K, Ca and Mg also showed a similar vertical distribution. However, extractable B content increased from the surface (5.8 μg/g) to about 10 cm depth (11.4 μg/g) and then declined gradually. Similar vertical distributions of pH, electrical conductivity and trace elements were also obtained in other studies (Hodgson and Buckley, 1975; Shaw, 1992; Shaw, 1996; Pillman and Jusaitis, 1997).

Organic matter builds up as succession proceeds. Results showed that nutrients (N and P) and organic C had started to accumulate on the surface of fly ash lagoon (Fig. 2.2). In the early stages of ecosystem development on raw soil materials, there is an increase in the fertility of the soil in terms of nutrients available to plants (Crocker and Major, 1955). The increase was also found in other fly ash heaps (Rippon and Wood, 1975; Shaw, 1992). The ash surface consisted of a crust of algal mat and dried moss (field observation). There was little vertical mixing, resulting in an accumulation of organic matter on the surface and a steep vertical gradient in nutrient level.

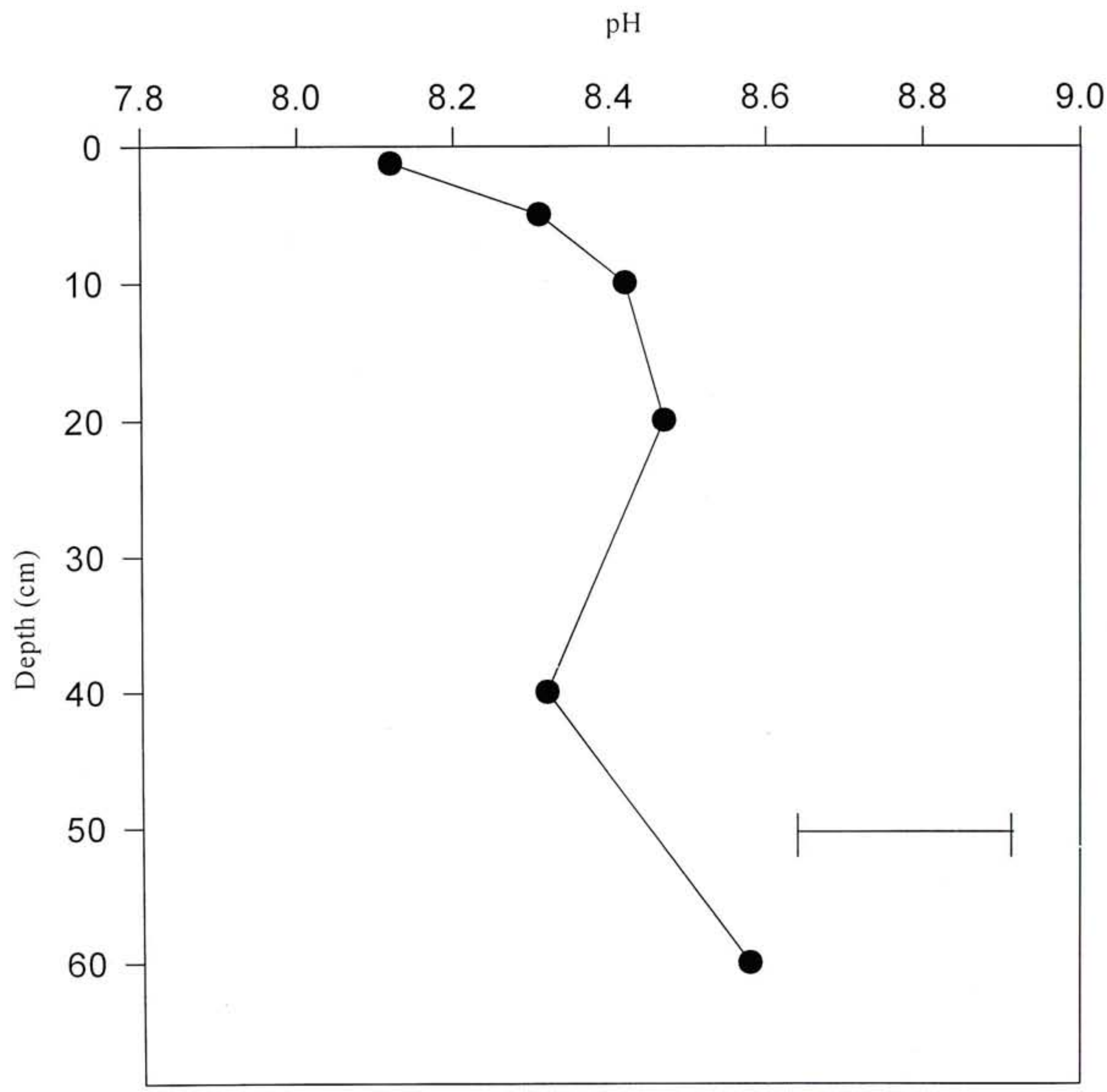

Fig. 2.1 Vertical profile of pH of fly ash from the middle lagoon. Horizontal bar denotes LSD at p<0.05.

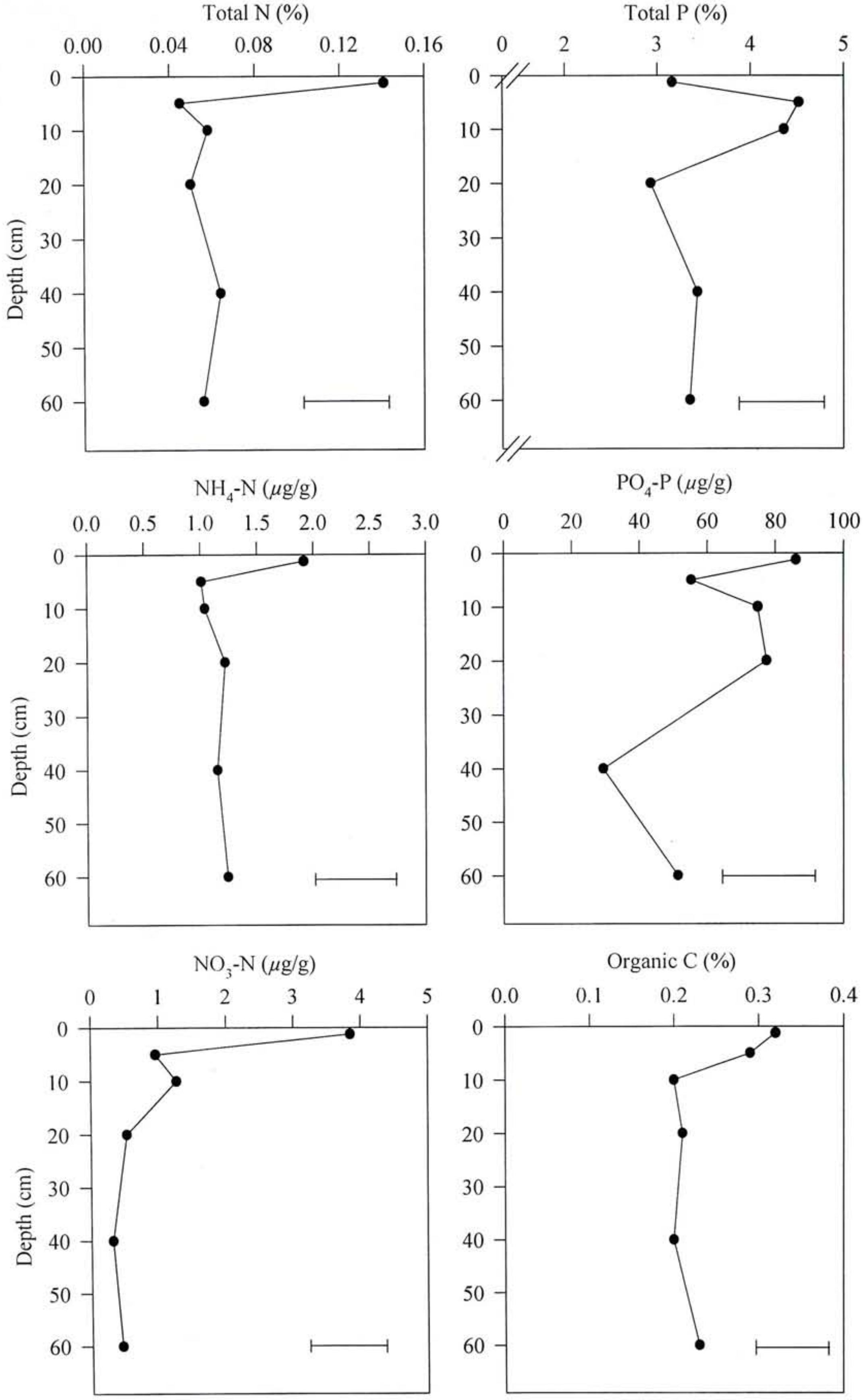

Fig. 2.2 Vertical profile of nutrients and organic carbon of fly ash from the middle lagoon. Horizontal bar denontes LSD at $p<0.05$.

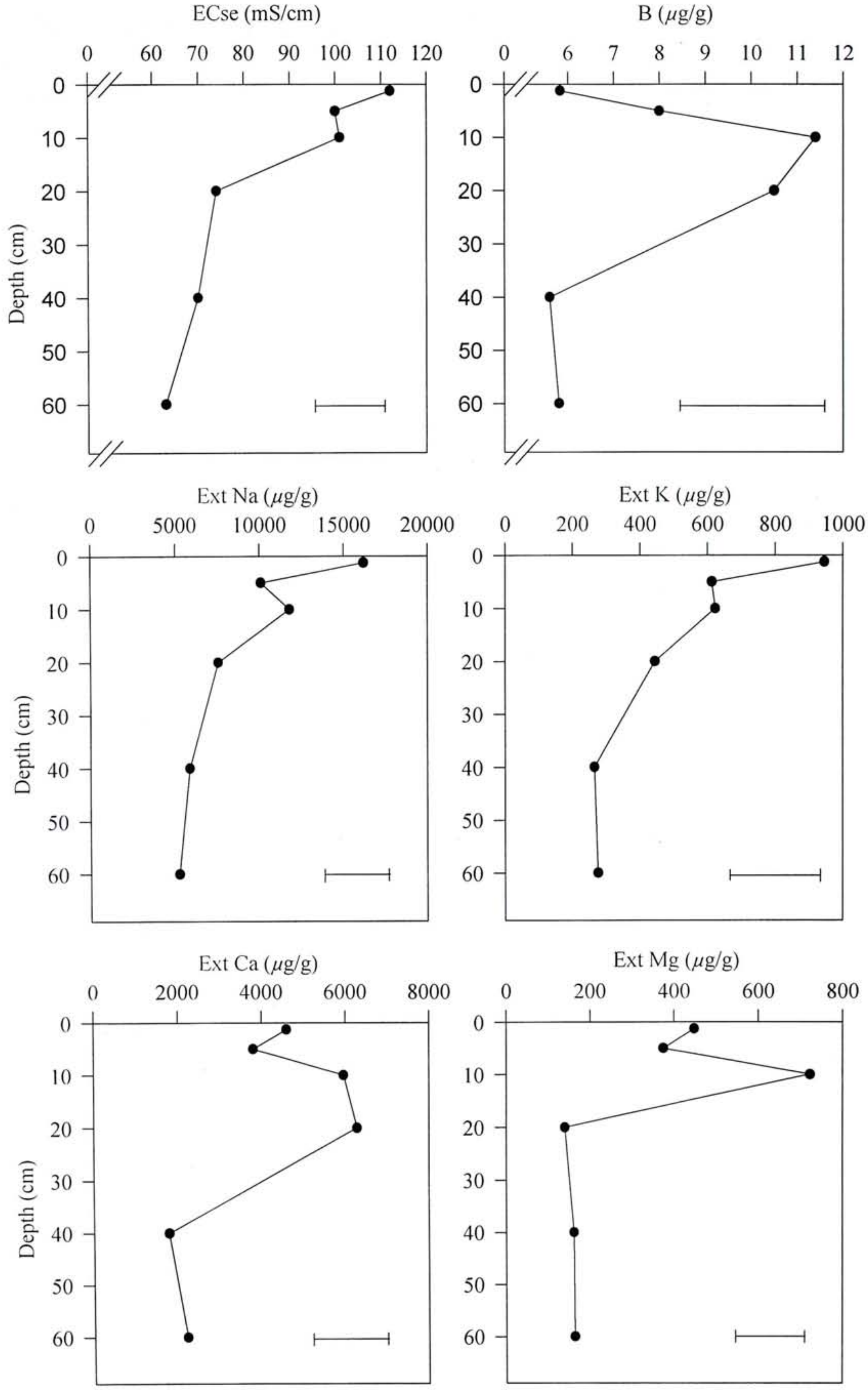

Fig. 2.3 Vertical profile of soluble salts and boron of fly ash from middle lagoon. Horizontal bar denotes LSD at $p<0.05$.

The build-up in organic C can lead to an increase in microbial activity (Rippon and Wood, 1975). Fly ash exposed to weathering is rapidly colonized by a range of bacteria but significant colonization by fungi and cellulolytic bacteria is delayed until organic matter starts to accumulate in the ash. The accumulation of organic matter is a continuing process, albeit a slow one (Shaw, 1992).

The electrical conductivity profile of fly ash (Fig. 2.3) represented a net upward fluxes of moisture and salts which is analogous to that in salt affected land. This phenomenon is usually found in saline soils coupled with poor drainage and upward movement of soluble salts during evaporation (Qureshi *et al.*, 1993; Dudley, 1994; Armstrong *et al.*, 1996). A crust was also found on the surface of fly ash heaps which have significantly higher levels of conductivity and soluble elements (Shaw, 1996). The underlying strata of the lagoon are marine mud and alluvial deposits on top of decomposed granite. A grout-filled, geotextile mattress was inclused on the outer seawalls of the lagoon to reduce the permeation of the decantrate via the normal rubble structure to the sea (Ashton, 1991; Ho and Chen, 1996). As a result, the lagoon would be, in a content extent, self-contained. Coupled with no drainage system for the removal of lagooned ash leachate, the soluble salts and mobile ions like nitrate can be taken up with water (Nye and Tinker, 1977) which could explain the accumulation of these substances on the surface of lagoon. In contrast, phosphate which is relatively immobile can be taken up from only a short distance resulting in no obvious changes in concentration along the profile.

Salinity decreases the water potential and reduces the amount of water available to plants. It disrupts plant nutrient acquisition by influencing nutrient (nitrate, phosphate and potassium) uptake and translocation, and by reduction of nutrient availability due to competition with major ions (i.e. Na^+ and Cl^-) in the substrate (Grattan and Grieve, 1992). High salinity also delays seed germination and reduces root to shoot ratio (Sen and Mohammed, 1994). As plant root densities generally decrease with soil depth, salinity in the upper part of the root zone affects more roots than the same concentration of salt in lower root zone. Since plants absorb water from zones of lower salinity, halophytic plants, especially those with deeper root systems, would have a better chance to survive in the fly ash lagoon.

Leaching controls salinity and B in soils and fly ash amended soil (Reeve *et al.*, 1955; Rhoades *et al.*, 1970; Bingham *et al.*, 1972; Phung *et al.*, 1979; Ghodrati, 1995). High salinity and B in some fly ash heaps can be reduced to non-toxic levels in two years by natural leaching (Hodgson and Townsend, 1973; Adriano *et al.*, 1980). However, unless the net flux of water over the leaching cycle is downward (for example, by installation of a drainage system), salts are carried to the surface with the water through evapotranspiration which occurs in saline-sodic soils (Wood, 1995; Armstrong *et al.*, 1996). The rate of decrease of soluble constituents in areas with high water table and/or impeded drainage may well be considerably lower (Jones and Lewis, 1960).

Apart from leaching, diffusion barriers such as clay caps have been used in reclamation programs to limit the diffusion of sodium and B into the surface (Munshower, 1994). Soil (as much as 1 m) is placed over the clay cap to support plant growth. Using soil to cover the ash surface has been practised. Covering with a 30 cm layer of soil and applying fertilizer at rates higher than normal are essential for economic crop production (Hodgson and Townsend, 1973). The total depth of root zone materials over toxic, saline coal ash should be at least 70 cm in semiarid western rangelands (Munshower, 1994). If the land is to be returned to forest or shrub land, the depth of root zone material should be increased.

2.3.4 **Vegetation survey**

Generally, the vegetation on the fly ash lagoon was patchy (Plate 2.2). Bare ground occupied over 80% of the lagoon surface (field observation). Twelve plant species from 5 families were recorded from the middle fly ash lagoon (Table 2.3). Among them, four species belonged to family Compositae; four Gramineae, two Cyperaceae, one Tamaricaceae and one Chenopodiaceae.

Leptochloa fusca (Plate 2.3) was the dominant plant species with the highest importance value (88.8). The relative density (55.2) and relative dominance (31.7) value were the highest which indicated that the population and coverage of this plant species were very high. But when considering the low relative frequency, most of this species was distributed not very evenly. It would be more likely to find this species in the middle of the lagoon than in the periphery. *Fimbristylis polytrichoides* (Plate 2.4) ranked second while *Tamarix chinensis* (Plate 2.5) was the third. Although

Table 2.3 Relative density, relative dominance, relative frequency and importance value of plant species naturally colonizing the middle fly ash lagoon.

Plant species	Family	Relative density	Relative dominance	Relative frequency	Importance* value
Leptochloa fusca	Gramineae	55.2	31.7	1.8	88.8
Fimbristylis polytrichoides	Cyperaceae	26.6	19.9	17.9	64.4
Tamarix chinensis	Tamaricaceae	5.4	28.8	25.9	60.1
Conzya bonariensis	Compositae	5.3	6.8	7.4	19.5
Cyperus javanicus	Cyperaceae	2.0	4.3	8.6	14.9
Phragmites communis	Gramineae	4.1	7.3	1.8	13.2
Pluchea indica	Compositae	1.4	1.0	2.5	4.9
Vernonia cinerea	Compositae	<0.1	0.2	0.6	0.8
Eclipta prostrata	Compositae	<0.1	0.1	0.6	0.7
Paspalum scrobiculatum	Gramineae	<0.1	0.1	0.5	0.6
Chloris barbata	Gramineae	<0.1	0.1	0.4	0.5
Chenopodium ambrosioides	Chenopodiaceae	<0.1	0.1	0.2	0.3

* Important value is the summation of relative density, relative dominance and relative frequency.

Plate 2.1 Vegetation surveying on fly ash lagoon.

Plate 2.2 Overview of a part of the middle fly ash lagoon.

Plate 2.3 *Leptochloa fusca* on fly ash lagoon.

Plate 2.4 *Fimbristylis polytrichoides* on fly ash lagoon.

Plate 2.5 *Tamarix chinensis* on fly ash lagoon.

Tamarix chinensis was the third dominant plant species on the lagoon (in terms of importance value), got the highest relative frequency value which suggests that the distribution of this plant species on the lagoon was so wide that it was likely to be sampled. The relative frequency of *Cyperus javanicus* was 8.6 (the third rank among other plants) although the importance value ranked fifth.

Due to the limited population sampled, the following plant species have low importance values: *Pluchea indica*, *Vernonia cinerea*, *Eclipta prostrata*, *Paspalum scrobiculatum* (found mainly in flooded area of the lagoon), *Chloris barbata* and *Chenopodium ambrosioides*. Additional species also occurred on the edge of the lagoon which had not been included in the calculation of importance value. They included *Eleucine indica*, *Sporobulus virginicus*, *Rhynchelytrum repens*, *Emilia sonchifolia*, *Sonchus arvensis*, *Solanum nigrum*, *Macaranga tanarius* and *Ficus variolosa*.

Some of the plant species such as *Phragmites communis*, *Cyperus* sp. and *Chenopodium* sp. are commonly found in a local salt marsh (WWF, 1989) while *Tamarix chinensis* was found in this local natural habitat for the first time. They belong to families (Gramineae, Cyperaceae, Chenopodiaceae and Tamaricaceae respectively) which are reported to be families of natural halophytes in China (Hu and Chin, 1993). In other studies on ash lagoons, many plant species were salt-tolerant, halophytic species (Hodgson and Townsend, 1973; Gonsoulin, 1975; Brieger *et al.*, 1992; Tripathy and Sahu, 1995; Shaw, 1996). It is not clear whether vegetation on fly ash lagoons develops tolerance to B (or other metals) or the species are already broadly tolerant to high B content. From visual observation, plants were apparently healthy and occasionally burning of leaf tips was found, which is a symptom of B phytotoxicity. In a preliminary study, Cu, Pb and Zn were accumulated in *Tamarix chinensis* and *Fimbristylis polytrichoides* on a fly ash lagoon (Mok, 1994). Bioaccumulation of heavy metals and other toxic elements by plants (e.g. *Cyperus* sp. and *Andropogon* sp.) growing on the ash was also demonstrated (Guthrie and Cherry, 1979; Cherry and Guthrie, 1979)

Leptochloa fusca was the dominant plant species in the fly ash lagoon. The dominance of this species might be attributed to its high salt tolerance. One of the adaptational features of the species is the existence of salt glands (a unique anatomical feature that allows the plant to selectively excrete salt from its leaf) in leaves. It was found that a substantial proportion of the salt entering a leaf can be excreted through salt glands (Gorham, 1987). It has been speculated that salt excretion through these glands prevents the build-up of salt in mature leaves, so prolonging their active photosynthetic life.

Internal redistribution of ions occurs in all plants, but may be particularly important in maintaining the required ionic balance in tissue of halophytes. Retranslocation and root efflux of both Na^+ and Cl^- occur in *Leptochloa fusca* and may be important processes in determining leaf salt levels (Bhatti and Wieneke, 1984). Accumulation of proline (N-containing compounds) and tissue dehydration were also reported in *Leptochloa fusca* in response to imposed high salt treatments (Sandhu *et al*. 1981).

Tamarix chinensis was found for the first time in a local natural habitat. It is suggested that the seeds of *Tamarix* were transported to the ash lagoons by migratory birds (Mok, 1994). Tamarisks (also known as salt-cedars) are native to arid areas of Asia minor, north-western India and northern and north-eastern Africa (Baum, 1978). In their native habitats, propagation is assumed to be mostly vegetative (Waisel, 1960) although establishment from seeds after summer rains has been reported. The seeds have a pappus, making them suitable for wind transportation, but they are viable for only a few weeks. It is a halophytic or xerophytic shrub with multiple stems and slender branches. Salt glands have been reported in plants from the family Tamaricaceae (Berry and Thomson, 1967; Berry, 1970). This coupled with its deep and extensive root system makes *Tamarix* spp. more adapted to the high salt environment. The salts concentration on the foilage may be up to 50 times that in the root water supply. It is hypothesized that salt excretions serve as allelopathic agents (which is too saline for establishment and survival of most other plant species) in habitats occupied by *Tamarix* spp. (Siegel and Brock, 1990). In addition to salt tolerance, *Tamarix* spp. are resistant to industrially generated gases, including sulfur dioxide (Smirnov, 1983). Survival of mature *Tamarix* spp. roots with crowns submerged in still water for 98 days and with total plant submerged for 70 days has been reported (Warren and Turner, 1975). This ability to survive inundation in low oxygen conditions contributes to the adaptability of this plant to waterlogged condition such as the intermittent floodings on the fly ash lagoon. The invasive characteristics of Tamarisks along the shoreline were reported in several studies (Dreesen and Wangen, 1981; Griffin *et al.*, 1989; Brock, 1994). It has also been used in determining the impact of effluents from a coal-fired power plant (Dreesen and Wangen, 1981). Due to its tolerance to a variety of stress conditions, *Tamarix* spp. have been suggested to be used in revegetation of degraded saline and/or sodic environments among many of the halophytes (Singh, 1989; Forestry Department, 1993; Qureshi *et al.*, 1993; Llerena, 1994; Malcolm, 1994).

It was noticed that vegetation on fly ash lagoon was patchy and most plants were distributed on the periphery of the lagoon rather than the middle part. *Leptochloa fusca* was one of the species found easily in the middle of lagoon where flooding is common. Others included *Tamarix chinensis*, *Paspalum scrobiculatum* and *Phragmites communis*. Only three clones of *Phragmites communis* were found during the site visit, notably forming 'green islands'. They spread vegetatively by means of rhizomes. Difficulty arises in quantifying this species. If considering each clone as one individual (due to the extensive rhizome) rather than separated shoot above ground, the relative density of *Phragmites* would be reduced drastically. One of the potential advantages of the presence of rhizome is the transport of photosynthate between ramets in less-saline microsites and those in saline microsites. Thus, in a heterogeneous environment, ramets in unfavourable sites may be buffered against their immediate surroundings by better situated neighbors. The possession of persistent underground storage organs would allow nutrients to be stored during winter and start growth earlier (Jefferies and Rudmik, 1984). The clone could also produce a high moisture retention microsite by their closely packed ramets.

The importance of physical features of fly ash on the establishment and subsequent colonisation was readily observable on the surface of the lagoon during the period of the vegetation survey. The fly ash had dried up to produce a hard smooth crust over the surface, which is impenetrable to root colonization (see Table 2.1 for penetration resistance). The further drying of the ash resulted in the crust splitting to form polygons with cracks 1 to 2 cm wide on the surface (Plate 2.5). These cracks provide niches in which seedlings become established especially when wetted after rains. At the time of survey, *Tamarix chinensis*, *Fimbristylis polytrichoides* and *Conzya bonariensis* were usually confined to the polygonal cracks. Vegetation grown on cracks has been reported on a fly ash lagoon (Brieger *et al.*, 1992) and a calcareous wastes from the salt and alkali industry (Lee and Greenwood, 1976). It is suggested that the cracks create a favourable niche for seed germination and seedling establishment by encouraging leaching of salts and storage of water, seed and litter (Cotts & Redente, 1995). These cracks also provide an improved and protected microsite to keep seedlings from desiccation. A rough soil surface is sometimes better than any other treatment suggesting ways of economizing in seedbed preparation (Harper and Benton, 1966). The rationale of the microsite or niche formation has been applied to dryland revegetation by using a land imprinting technique (Dixon, 1990) and salt-affected soils halophyte establishment by a specially developed direct seeding machine called Mallen niche seeder (Malcolm and Allen, 1981). Surface amelioration

Plate 2.5 Plants growing along the cracks on fly ash lagoon.

treatment by addition of compost and mulch was outstanding in terms of biomass production of transplants on fly ash lagoons (Jusaitis and Pillman, 1997).

The physical environment on the fly ash lagoon resembles that of a salt marsh (i.e. high salinity and water-logging). Common salt marsh vegetation was found on the fly ash lagoon. Probably, an alternative ecological option to revegetate fly ash lagoons is the creation of a wetland habitat as has been done for coal slurry ponds (Thompson, 1988). The feasibility and effectiveness of the creation of wetlands on the fly ash lagoon requires further study. In another study, the use of seedbank substrates, which contain pre-adapted seeds like halophytes and symbiotic microflora such as VA mycorrhizas and rhizobia from disused fly ash sites to initiate colonization of fresh fly ash seems promising (Shaw, 1996). Xerophytes and halophytes performed optimally in a South Australian fly ash lagoon (Jusaitis and Pillman, 1997). Further investigation in revegetating fly ash lagoons by using halophytes and saltmarsh vegetation would be rewarding.

2.4 **CONCLUSIONS**

The factors limiting vegetation growth on fly ash lagoons might include high pH, salts and B content, deficiencies in nutrients and organic matter as well as poor physical properties. Among them, high contents of salts and B seem to be the major limiting factors to plant growth. The dominance of halophytic plants (*Leptochloa fusca*, *Fimbristylis polytrichoides* and *Tamarix chinensis*) on the fly ash lagoon coincides with the results of chemical analysis. Before successful revegetation, high salts and B conditions should be removed preferably followed by an addition of organic matter to improve the nutrient status and physical properties so as to create a self-sustained ecosystem.

Chapter 3 **GREENHOUSE PLANT SELECTION AND AMELIORATION TRIALS ON LAGOONED FLY ASH**

3.1 **INTRODUCTION**

Ecosystem development directly on wasteland substrates is a process of 'primary succession' whether it is allowed to occur naturally or is artificially assisted (Bradshaw, 1983). From a practical point of view, speed of attainment, cost, reliability and stability are important considerations in land reclamation and revegetation. Except for speed, nature meets these criteria unassisted through natural succession. To accelerate succession on wastelands, it is necessary to understand the factors limiting (arresting) succession at each point of its progress and to relieve them so as to optimize the environment, both for individual species and for the entire ecosystem.

Through analytical procedures as described in Chapter 2, the factors limiting vegetation growth on a fly ash lagoon might include poor physical properties, deficiencies in nutrients and organic matter as well as high pH, salts and B content. The underlying problems of wastelands (which can be physical, nutritional, toxicological and biological) and their treatments (either short or long term) have been summarized in Table 1.3 (Bradshaw, 1989). It is significant that nearly all the long term solutions are part of ecological processes involving vegetation.

However, the establishment of species by natural processes, in general, tends to be slow and stochastic. Analysis of natural successions on natural and artificial substrates suggests that one of the most important factors limiting the rate of development is the problems of immigration (Ash *et al.*, 1994). Once propagules of the appropriate species arrive, other problems are the selection of the adapted species, and species which can evolve adaptation to the extreme conditions will finally establish. Therefore, it is a normal practice that selected species are introduced artificially as has been done by Scanlon and Duggan (1979), McMinn *et al.* (1982) and Carlson and Adriano (1991), using a variety of techniques (the so called adaptive approach) to ensure effective seed or plant placement.

However, there is a need to find species tolerant of the different conditions (Jefferies *et al.*, 1981). Plant species have been selected for their tolerance on fly ash, based on their tolerance to high B and soluble salts as well as nutrient stress (Hodgson and Townsend, 1973; Hodgson and Buckley, 1975). Species naturally adapted to saline conditions establish very satisfactorily on fly ash (Hodgson and Townsend, 1973; Brieger *et al.*, 1992; Shaw, 1992; Shaw, 1996; Jusaitis and Pillman, 1997). Thus, salt tolerant species (grasses or trees) may show promise in the revegetation of fly ash lagoons.

Analytical procedures will give information, relatively quickly, that can be used to predict the potential of waste material as a growth medium for plants. The crucial test, however, is to see whether plants will grow on the material, and how it can be altered to improve growth. This can be done very easily by pot trials. If designed intelligently, and conducted correctly, they can yield precise information (Bradshaw and Chadwick, 1980).

In the present experiments, a greenhouse pot trial was conducted to screen grass and tree species which could grow on lagooned fly ash. A second pot trial, using the growth response of *Lolium perenne*, which is a nutrient demanding plant and often planted in reclamation work, was carried out to determine the most probable limiting factor(s) (among phytotoxicity, nutrient deficiency and poor physical condition) to plant growth of lagooned fly ash. The effects of macro-nutrients (N, P and K) on plant growth were further examined in another pot trial.

3.2 MATERIALS AND METHODS

3.2.1 Collection of lagooned fly ash and planting materials

Fly ash was collected from the surface (0-15 cm) of the middle lagoon at Tsang Tsui in April 1995. A garden soil (for comparison of plant performance) and sawdust (as a physical ameliorant) were obtained from a nursery and a carpentry workshop respectively in the campus of The Chinese University of Hong Kong. The lagooned fly ash and garden soil were sieved through an 1 cm mesh sieve to remove gravel and debris.

Seeds of *Lolium perenne*, *Cynodon dactylon* and *Chloris gayana* were purchased from commercial seed suppliers, while seeds of *Leptochloa fusca* were collected from the middle fly ash lagoon. Tree seedlings of one to twelve month old (Table 3.1) were obtained from nurseries of the Urban Council (Tai Po and Tsuen Wan) and Agriculture and Fisheries Department (Tai Tong) respectively.

3.2.2 **Plant selection trial**

Twenty seeds of the four grass species were sown directly on 7 cm diameter pot (350 ml in volume) containing either a garden soil or lagooned fly ash alone. The soil was a sandy loam (pH = 6.4 and EC = 1.2 mS/cm) while fly ash had a pH of 8.3 and EC of 95 mS/cm. The pots were kept in a greenhouse and arranged in split-plot design based on randomized blocks. There were three replicates for each treatment. They were watered daily. Seedling emergence was observed each day. Since no seed germination of the grasses was observed in the fly ash pots after 14 days, 10 seedlings of the four plant species were prepared and transplanted to the pots containing fly ash and garden soil respectively. The seedling survival was recorded after 14 days.

Twenty five species of trees were tested. Uniform size seedlings of each tree species were selected and transplanted to pots (15 cm in diameter and 2.7 L in volume) containing either garden soil or lagooned fly ash (Plate 3.1). The root ball was not disturbed while repotting into the larger pot. The pots were arranged in split plots (based on a randomised block design) in a greenhouse. There were five replicates for each treatment. Fertilizer (1.2 g Nitrophoska per pot) was added once to each pot at the beginning of the growth experiment. The pots were watered daily. Plant height and survival were measured at intervals over the experimental period of 120 days.

Table 3.1 Tree species selected for greenhouse screening trial on lagooned fly ash.

	Tree species	Family	Salt tolerant	N-fixing
1	*Cerbera manghas*	Apocynaceae	√	
2	*Cassia surattensis*	Caesalpiniaceae		√
3	*Casuarina equisetifolia*	Casuarinaceae	√	√
4	*Juniperus chinensis*	Cupressaceae	√	
5	*Juniperus conferta*	Cupressaceae	√	
6	*Thuja orientalis*	Cupressaceae		
7	*Macaranga tanarius*	Euphorbiaceae	√	
8	*Sapium discolour*	Euphorbiaceae		
9	*Liquidambar formosana*	Hamamelidaceae		
10	*Machilus ichangensis*	Lauraceae		
11	*Hibiscus tiliaceus*	Malvaceae	√	
12	*Acacia auriculaeformis*	Mimosaceae		√
13	*Acacia confusa*	Mimosaceae	√	√
14	*Acacia mangium*	Mimosaceae	√	√
15	*Leucaena leucocephala*	Mimosaceae	√	√
16	*Ficus microcarpa*	Moraceae	√	
17	*Myrica rubra*	Myricaceae		
18	*Eucalyptus torelliana*	Myrtaceae	√	
19	*Melaleuca leucadendron*	Myrtaceae	√	
20	*Syzygium jambos*	Myrtaceae		
21	*Tristania conferta*	Myrtaceae		
22	*Keteleeria fortunei*	Pinaceae		
23	*Pinus elliottii*	Pinaceae		
24	*Podocarpus macrophyllus*	Podocarpaceae		
25	*Cunninghamia lanceolata*	Taxodiaceae		

Plate 3.1 Pot trials of tree seedlings in greenhouse arranged in split pot design.

3.2.3 **Amelioration trials**

The responses of *Lolium perenne* cv. Taya to different treatments were assessed in two greenhouse pot trials. Seeds were germinated in perlite and 10 one week old seedlings were transplanted to lagooned fly ash in 10 cm diameter pot (600 ml in volume).

In the first trial, lagooned fly ash was either (1) untreated, (2) added with fertilizer (100 kg N/ha) as Nitrophoska (NPK; 15:15:15), (3) washed with 0.5% acetic acid one times followed by water three times and (4) mixed with sawdust (ash : sawdust = 8:1 w/w) in factorial combinations. A garden soil was included as a reference. Each treatment was replicated three times and the pots were arranged in randomised blocks in a greenhouse. The pots were watered daily and harvested after 60 days. The dry weight of shoots were determined after being oven dried at 60°C for one week. The edaphological properties (pH, EC, Na, K, Ca, Mg, B) of untreated ash and washed ash were determined.

The second trial examined the response of *Lolium perenne* to N, P and K on lagooned fly ash. Washed ash was put in 10 cm pot (600 ml in volume), and the following treatments were established; (1) N, P and K (complete fertilization), (2) P and K (without N), (3) N and K (without P), (4) N and P (without K). Additional treatments included an unfertilized control and a garden soil receiving N, P and K. The rates for the treatment were approximately equivalent to 500 N kg/ha, 225 P kg/ha and 290 K kg/ha (Table 3.2). The treatments were replicated three times and arranged in

Table 3.2 Amount of nutrients added to washed lagooned fly ash in 9.6 cm pots.

	Fertilizer treatment	NH_4NO_3 (ml)	KH_2PO_4 (ml)	K_2SO_4 (ml)	NaH_2PO_4 (ml)
		10 g/L	20 g/L	15 g/L	20 g/L
Ash	NPK	10	10	-	-
Ash	PK (without N)	-	10	-	-
Ash	NK (without P)	10	-	10	-
Ash	NP (without K)	10	-	-	10
Ash	(without NPK)	-	-	-	-
Soil	NPK	10	10	10	10

randomized blocks. Plants were harvested after six weeks and oven-dried at 60°C for one week for the determination of yield of shoots and roots.

3.2.4 **Statistical analysis**

Untransformed data of plant growth were subjected to one way analysis of variance (ANOVA) at the 0.05 significance level to test the difference among various treatments. Least significant difference (LSD) for the means was calculated where necessary at the 0.05 significance level. All statistical analyses were performed by means of SPSS for Windows Release 6.0 (SPSS, 1989).

3.3 **RESULTS AND DISCUSSION**

3.3.1 **Plant selection trial**

All the grasses tested including *Lolium perenne*, *Cynodon dactylon*, *Chloris gayana* and *Leptochloa fusca* were unable to germinate on the lagooned fly ash. Their seedlings were prepared later and transplanted onto the lagooned ash and garden soil. After one week, no seedlings survived on the fly ash but all survived on the soil.

The grasses selected for the present plant screening trial are considered as halophytes in various studies (Russell, 1976; Gallagher, 1985; Maas, 1985). The high salt content (95 mS/cm) in lagooned fly ash could explain the inhibition of plant growth even though *Leptochloa fusca* were collected from the lagoon. The establishment of vegetation on the fly ash lagoon would be not only due to the level of adaptability of the plant to site factors but also the presence of suitable microhabitats where the edaphological characteristics are more favourable to plant growth. A significant reduction in electrical conductivity in vegetated ash as compared to adjacent bare areas was recorded on a fly ash lagoon (Lou, 1991). The effects of chemical variation on vegetation distribution on wasteland were also reported (Snaydon, 1962; Tasker and Chadwick 1978). Thus, to revegetate the lagooned fly ash simply by using salt tolerant grasses may be of help but not necessarily the most promising method.

During the testing period, most of the tree species listed on Table 3.1 were unable to grow on lagooned fly ash except five salt tolerant species: *Melaleuca leucadendron* (Plate 3.2), *Leucaena leucocephala* (Plate 3.3), *Casuarina equisetifolia* (Plate 3.4), *Cerbera manghas* (Plate 3.5) and *Hibiscus tiliaceus* (Plate 3.6). The latter two are native species.

Compared to 100% survival rate in garden soil, their survival rate (5 individuals of each species) varied from 20% to 60% (Table 3.3). Among them, the relative growth percentage of *Melaleuca leucadendron* was the greatest (100%) and *Hibiscus tiliaceus* the least (11%).

Despite the fact that direct comparison of the relative growth percentage between species would not be legitimate since the age, size, pre-condition and the root ball size of tree species were different, the relative growth percentage could still give a good indication of the performance of the species on fly ash. Most of the plants

Plate 3.2 *Melaleuca leucadendron* in pots containing fly ash (left) and soil (right).

Plate 3.3 *Leucaena leucocephala* in pots containing fly ash (left) and soil (right).

Plate 3.4 *Casuarina equisetifolia* in pots containing fly ash (left) and soil (right).

Plate 3.5 *Cerbera manghas* in pots containing fly ash (left) and soil (right).

Plate 3.6 *Hibiscus tiliaceus* in pots containing fly ash (left) and soil (right).

Table 3.3 Growth (increase in tree height) and survival of selected species on lagooned fly ash and soil.

	Growth (cm)		Relative growth* (%)	Survival (%)	
	Lagooned ash	Soil		Lagooned ash	Soil
Melaleuca leucadendron	10.0	10.0	100	60	100
Leucaena leucocephala	1.3	3.2	41	60	100
Casuarina equisetifolia	17.0	49.3	34	20	100
Cerbera manghas	2.6	16.4	16	60	100
Hibiscus tiliaceus	1.0	9.0	11	20	100

*Relative growth (%) computed as (growth on lagooned fly ash/growth on soil)x100%.

selected for the screening test showed some abnormalities on lagooned fly ash, such as reduced vigour and leaf symptoms like marginal scorch, leaf tip necrosis and chlorosis, indicating nutrient deficiencies and/or toxicities of toxic elements, probably salts and B. That might explain the low survival rate of the tree species used. It might not be promising to simply transplant tree seedlings on to the ash lagoon due to the low survival rate. Further improvement should be required before commencing a large scale field trial of tree planting on lagooned fly ash or massive mortality of plants would result.

Since no comprehensive study of B tolerance of locally available woody species has been conducted, which might serve as a guide to the selection of trees for planting on fly ash, selection criteria for tree species was based on results of previous planting trials and their reported tolerance to salt. Some of the tree species for the present screening trial are categorized as salt spray tolerant (Webb, 1991). Leguminous trees were included with the intention to improve the nitrogen status of the fly ash lagoon. However, the result was not very satisfactory since the only leguminous tree survived in the screening trial was *Leucaena leucocephala*. The other four surviving tree species are all salt tolerant. *Casuarina equisetifolia* which is frequently planted on foreshores and beaches in Hong Kong (Thrower, 1988), is highly tolerant of salty soil (Rogers, 1982) and commonly used in reclamation of saline lands (Forestry Department, 1993). Periodic inundation by seawater does not harm them. *Cerbera manghas* is a common strand plant widely distributed along the coasts of tropical Asia (Jim, 1990). It is found naturally in mangroves as well as sandy and rocky shore habitats. It can withstand saline soils that may be periodically inundated by seawater, and a lot of sea sprays. *Hibiscus tiliaceus* is usually found along the edge of mangrove forests and coastal sites.

Due to its tolerance to stressful conditions, *Leucaena leucocephala* has been identified as a most promising species for afforestation on alkaline wasteland and saline-sodic conditions (Singh, 1989; Qureshi *et al*., 1993). Together with *Casuarina equisetifolia* which has a symbiotic association with N-fixing organisms (and vesicular-arbuscular endomycorrhiza), they may serve as pioneer species, not only fixing N for their own use but also enriching and stabilizing the soil as well as facilitating the establishment of other plant species. The use of N-fixing species as 'nurse' crops for other species growing on fly ash may be the most satisfactory technique for establishing a tree cover unless large quantities of N-rich organic matter are imported to the site to be reclaimed (Hodgson and Townsend, 1973).

3.3.2 **Amelioration trials**

In the first amelioration trial, *Lolium perenne* was subjected to 4 treatments (in factorial combinations) and a soil reference and the results were shown in Figure 3.1. All seedlings died when grown in ash alone and in ash with the addition of nutrients, sawdust or both. Growth was obtained in pots containing fly ash that had been washed irrespective of amendments. The greatest yield (0.82 g dry weight/pot) was obtained in pots with fertilized washed ash. However, ash treated with sawdust, significantly reduced yield compared to corresponding treatments without sawdust. This reduction

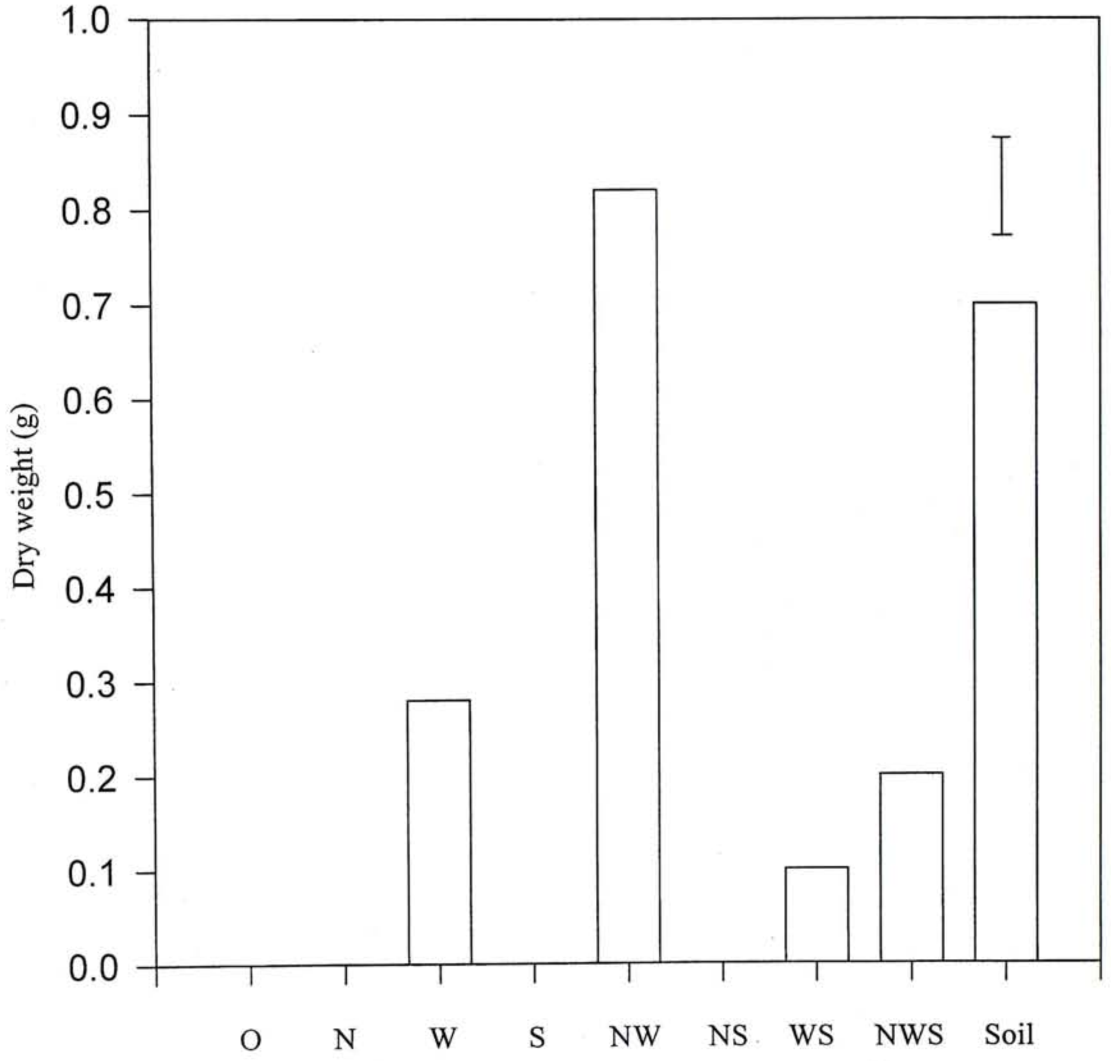

Fig. 3.1 Effect of fertilization, washing and physical amendment on growth of *Lolium perenne* on lagooned fly ash. Vertical bar denotes LSD at $p<0.05$. O, N, W and S represent control, treatment of fertilizer, washing and saw dust addition respectively.

of dry weight could be due to the presence of toxic substances like wood preservatives in the sawdust and/or the increase in C/N ratio in the lagooned ash which outweighed the beneficial effect(s) of physical improvement and dilution effect.

The effect of washing on the edaphological properties of lagooned fly ash is shown in Table 3.4. After washing, all the parameters tested were reduced significantly ($p<0.05$) in ash; e.g. pH was reduced from 8.4 to 7.6 and extractable B from 21.8 to 2.3 ($\mu g/g$). Soluble salts (e.g. Na, K, Ca and Mg) also declined substantially as reflected from the 10 fold decrease in electrical conductivity.

The effect of nutrient addition on plant growth is shown in Table 3.5. With reference to complete fertilization, significant growth reduction ($p<0.05$), in terms of total dry weight per pot was observed in fertilized ash without N (0.77 g), without P (0.62 g) and without N, P & K (0.53 g). Growth reduction in fertilized ash without additional K was not significant. It is, therefore, suggested that N and P were limiting in fly ash for plant growth which was consistent to the results of chemical analysis (Table 2.2). Growth of *Lolium perenne* on lagooned fly ash with complete fertilization (1.61 g per pot) was significantly lower than that on complete fertilized soil (2.71 g per pot) with lower dry weight in shoot, suggesting the presence of inhibiting factor(s) associated with the ash material even after washing or fertilization was not enough, influencing the growth of shoots especially.

Table 3.4 Effect of washing on the edaphological properties of lagooned fly ash (mean of 3 replicates).

	Lagooned ash	Washed lagooned ash
pH	8.4 (0.1)*	7.6 (0.1)
EC (mS/cm)	57.0 (0.9)	5.1 (0.1)
Ext Na (μg/g)	7030 (20)	1720 (0)
Ext K (μg/g)	778 (7)	151 (2)
Ext Ca (μg/g)	4060 (30)	728 (4)
Ext Mg (μg/g)	100 (1)	85 (0)
Ext B (μg/g)	21.8 (1.1)	2.3 (0.1)

*Standard deviation is parenthesized.

Table 3.5 Effect of fertilizer treatment on weight and shoot to root ratio for grass grown on washed lagooned fly ash.

	Fertilizer treatment	*Lolium perennial* (g dry wt)			Shoot : root ratio
		Shoot	Root	Total	
PFA	NPK	0.64	0.97	1.61	1.52
PFA	PK (without N)	0.25	0.52	0.77	2.03
PFA	NK (without P)	0.35	0.27	0.62	0.77
PFA	NP (without K)	0.70	0.65	1.34	0.93
PFA	(without NPK)	0.21	0.33	0.53	1.57
Soil	NPK	1.52	1.19	2.71	0.78
LSD ($P<0.05$)		0.18	0.35	0.46	

Similarly, for the dry weight of root, there were no significant differences between ash treatments without K addition and ash with but significant growth reduction was observed in the absence of N, P and N, P & K.

Shoot to root relationships in plants tend to reflect the fertility and water status of soil. Generally, the shoot to root ratios were lower in those treatments without N than completely fertilized soil except completely fertilized ash.

It is typical in fly ash that N is totally absent (Bradshaw and Chadwick, 1980; Aitken *et al.*, 1984). The growth response of *Lolium perenne* reflected the limitation of N in fly ash by reduction of dry matter yield in the absence of N. Other studies also found that vegetation responded to the application of N especially in nutrient poor soils (Rees and Sidrak, 1956; Hodgson and Buckley, 1975; Piha *et al.*, 1995; Pillman and Jusaitis, 1997).

Although the P level in lagooned fly ash was generally high (Table 2.2), significant decreases in dry weight of *Lolium perenne* was observed in the absence of P indicating that P is limiting for plant growth. P is not in a form readily available to plants, presumably due to interactions with ash Al, Fe and with Ca in the case of highly alkaline ash (Townsend and Hodgson, 1973; Bradshaw and Chadwick, 1980; El-Mogazi *et al.*, 1988). Such inavailability of bound nutrients may also be species dependent as shown by the differential uptake of P by *Atriplex*, spinach and barley plants grown on fly ash containing abundant extractable P (Rees and Sidrak, 1956).

It is suggested that the application of N and P to fly ash during revegetation should enhance plant establishment and growth. Successive fertilization is possible but is expensive. Application of organic amendments like sewage sludge is very effective in supplying essential nutrients for revegetation (Hodgson and Townsend, 1973). N-fixing plants can even accumulate at least 100 kg N ha^{-1} $year^{-1}$ (Dancer *et al.*, 1977).

It seems that toxicities of the lagooned ash were the major limiting factor which retarded vegetation growth. The most likely plant growth inhibiting substances are soluble salts and B although other elements and factors not tested are possible. The addition of major nutrients to ash did not promote growth unless plant growth inhibiting substances had been removed. Addition of acid-treated fly ash to soil as compared to untreated ash showed better plant growth and lesser B uptake (Holliday *et al.*, 1958). Under such conditions, the deficiency of major nutrients is of secondary importance.

In view of B toxicity on soil, besides applying fertilization, amendments like lime to increase soil pH and thus promote adsorption of B from soil may provide a short term solution (Bartlett and Picarelli, 1973). In sodic soils, the B hazard can be ameliorated by addition of gypsum ($CaSO_4$), which can improve water infiltration and reduce B solubility. Under some circumstances, it may be possible to alleviate B toxicity in plants by applying Zn to soils (Graham *et al.*, 1986). By planting B tolerant species to take up and accumulate B as part of the revegetation strategy had been utilised (Banuelos *et al.*, 1993) but the feasibility of these alternatives on amelioration of fly ash requires further study.

However, successful establishment of suitable salt-tolerant trees on saline sites requires the use of appropriate pre- and post-planting strategies for reducing environmental stress. Amelioration of fly ash with either a layer of shale or soil improved survival and growth (Hodgson and Buckley, 1975). Other experiments using ash/shale mixtures demonstrated a similar effect (Hodgson and Townsend, 1973). A 50 -100 mm cover of either sandy topsoil or compost, stabilized with coarse organic mulch, hydromulch or erosion-control fabric supported good germination and plant growth on a fly ash lagoon (Jusaitis and Pillman, 1997). The soil or compost overlaid partially isolated plants from the toxic elements in ash. Survival and growth of transplants were also improved by increasing the root ball size (Hodgson and Buckley, 1975; Pillman and Jusaitis, 1997). With improved soil conditions, the growth response of species (including tolerant plants) used would be increased. The adaptive approach (development of adaptable species) and ameliorative approach (development of soil amendments) in the revegetation of waste lands are complementary, not mutually exclusive. Both approaches are important in the systematic approach to reclamation of waste land (see Fig 1.4).

3.4 **CONCLUSIONS**

In a pot trial, no germination and growth of grass species were obtained, while 5 out of 25 tree species survived on lagooned fly ash. The five species, namely *Melaleuca leucadendron*, *Leucaena leucocephala*, *Casuarina equisetifolia*, *Cerbera manghas* and *Hibiscus tiliaceus* are all halophytic plants. Salt-tolerant species may be better off in the revegetation of fly ash lagoons. In another pot amelioration trial, although it could not be confirmed that physical amendment could enhance plant growth, toxicities (mainly attributed to high soluble salts and B) were the major limiting factors for plant growth. The phytotoxic substances could be removed by washing. Once the toxicity factors were relieved, N and P deficiencies then became growth limiting and should be supplemented for the successful revegetation of fly ash lagoons.

Chapter 4 LEACHING OF SOLUBLE SALTS AND BORON FROM LAGOONED FLY ASH

4.1 INTRODUCTION

The trace element composition of fly ash depends on the composition of the coal combusted and the emission control design. Generally, trace element concentrations in fly ash are higher than their concentrations in coal (Klein *et al.*, 1975; Van Hook, 1979; Adriano, 1980) but are comparable to their corresponding concentrations in soils (Page *et al.*, 1979). The exceptions are B, Ca, Mg, Na, Mo and Se.

Of the constituents in fly ash, salts and B have been considered as the most likely candidates to cause phytotoxicity (Hodgson and Buckley, 1975; Collier and Greenwood, 1977; Tolle and Arthur, 1983; El-Mogazi *et al.*, 1988). From Chapter 2, salt and B contents of lagooned fly ash reached 120 mS/cm and 190 μg/g respectively which are classified as phytotoxic. Many plants can only tolerate a very narrow range of B (Adriano *et al.*, 1980; Keren and Bingham, 1985). Coal typically contains 5 to 200 μg/g B while it can be enriched to about 1500 μg/g in some ashes (James, 1982). B in fly ashes is in the form of boron oxides and borosilicate compounds and is regarded as being one of the most mobile elements in ash disposal systems (Jones, 1995).

It is possible to leach B and salts out from the root zone to levels suitable for plant growth because of the mobility of salts and B in lagooned fly ash. Previous studies have shown that salts and B in lagooned fly ash generally diminished with time (Hodgson and Townsend, 1973; Rippon and Wood, 1975; Adriano *et al.*, 1980; McMinn *et al.*, 1982). High soluble salts of fly ash can limit the establishment of vegetation unless the material is leached (Capp, 1978).

However, there is little specific information available on the amount of leaching needed to reduce salts and B in lagooned fly ash, especially those using seawater as the transporting medium. Most studies have focused on leachability of elements directly from raw fly ash (Dudas, 1981; Warren and Dudas, 1984, Warren and Dudas, 1985, Warren and Dudas, 1988). Some studies have beenconcerned about the beneficial effects of leaching on fly ash amended soil (Rhoades *et al.*, 1970; Bingham *et al.*, 1972; Phung *et al.*, 1979; Aitken and Bell, 1985; Ghodrati *et al.*, 1995). Other leaching studies have focused on the toxicity evaluation and trace elements composition of fly ash leachate (Van der Sloot *et al.*, 1989; Hjelmar, 1990; Reardon *et al.*, 1995; Albino *et al.*, 1996; Egemen and Yurteri, 1996; Lecuyer *et al.*, 1996) and the effects of pH on the leachability of metals from fly ash (Liem *et al.*, 1983; Hollis *et al.*, 1988; Fleming *et al.*, 1996).

Toxicities (mainly attributed to high soluble salts and B) were the major limiting factors for plant growth (Chapters 2 and 3). The present study was designed to investigate the feasibility of leaching salts and B from lagooned fly ash in laboratory columns and to determine the effects of different rates of leaching on the salts and B contents of ash and the effect of leaching on plant growth.

4.2 MATERIALS AND METHODS

4.2.1 Setup of leaching columns

Fly ash, collected from the surface (0-15 cm) of the middle lagoon at Tsang Tsui, was air dried, thoroughly mixed and packed in PVC columns (30 cm in height and 8 cm in diameter) to a bulk density of about 0.9 g/cm^3 which is comparable with the field condition (Fig. 4.1 and Plate 4.1). At the bottom of each column was a plastic disk with 40 holes (0.5 cm) to allow drainage. Before the column was filled with ash, the top of the bottom disk was covered with a filter paper for the retention of ash. A piece of filter paper was used to cover the top of the ash to minimize surface disturbances during addition of water.

4.2.2 Leaching regimes

Initially, fly ash columns were presaturated by introducing distilled water from the bottom. Once the ash surface became wetted, inflow was stopped. The ash was allowed to equilibrate for one week. One hundred and six ml (equivalent to 20 mm of rainfall) distilled water was applied to each column weekly with a cumulative volume equivalent to 0, 20, 40, 80, 200, 400 and 800 mm. The columns were kept in an air-conditioned room at 20-25°C and arranged in a randomized (complete) block design with three replicates. After leaching, the columns were dismantled and the fly ash was sectioned into 5 cm increments for the surface 10 cm ash and 10 cm increments for ash 10 - 30 cm. The ashes were air dried and analyzed for pH, soluble salts (electrical conductivity) and contents of Na, K, Ca, Mg and B.

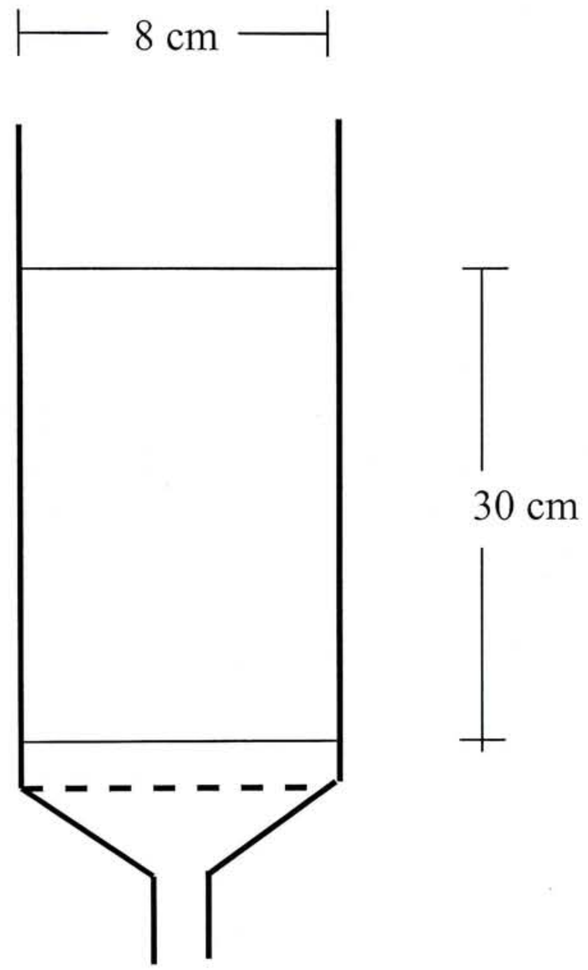

Fig. 4.1 Column used in leaching experiment (not in scale). Fly ash was packed to 30 cm height. Filter paper was placed on the ash surface and at the bottom.

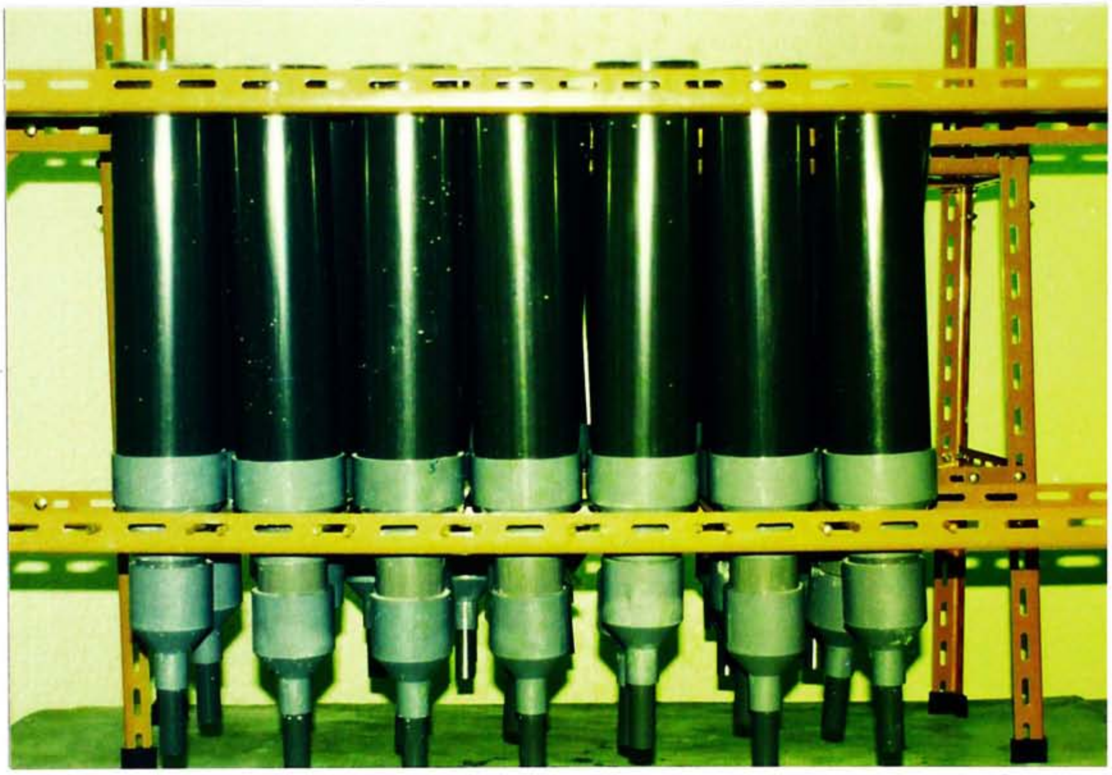

Plate 4.1 Setup of columns arranged in randomized complete block design.

4.2.3 **Growth of ryegrass on leached ashes**

Ash samples (surface 5 cm) after being leached with different amounts of water was sub-sampled and filled in 6 cm pots. Eight 1-week old seedlings of perennial ryegrass (*Lolium perenne* cv. Taya) were transplanted to each pot. The pots were arranged in randomized blocks in a greenhouse with three replicates and watered as necessary. Plants were harvested after 12 weeks. The harvested shoots were washed with distilled water to remove surface contaminants and oven-dried at 60°C for one week for dry weight determination.

4.2.4 **Chemical analysis on ashes**

Fly ash was analyzed for pH (pH meter, sample : 0.01 M $CaCl_2$ = 1:2.5 (w:v)); electrical conductivity (conductivity meter, saturation extract); extractable Na, K, Ca and Mg (Hitachi Z8100 Polarized Zeeman atomic absorption spectrophotometry after 1 M neutral ammonium acetate extraction); hot water extractable B (azomethine-H method with Lachat QuickChem AE Automated Ion Analyzer).

4.2.5 **Statistical Analysis**

Untransformed data of ash properties and plant growth were subjected to one way analysis of variance (ANOVA) at the 0.05 significance level to test the difference among different leaching regimes. Least significant difference (LSD) for the means was calculated where necessary at the 0.05 significance level. Correlation between dry weight of ryegrass and ash properties was carried out. All statistical analyses were performed by means of SPSS for Windows Release 6.0 (SPSS, 1989).

4.3 **RESULTS AND DISCUSSION**

4.3.1 **Leaching of soluble salts and B**

Before leaching commenced (0 mm leaching water), electrical conductivity (a measure of soluble salt content) of ash on the surface layer was the highest (530 mS/cm) and decreased with increasing depth, which is probably due to an upward movement of salts along with waterfront during the presaturation process (Fig. 4.2). Addition of increasing amounts of water washed the salts downward to the subsequent layers. After leaching with 200 mm or more, salt content was reduced to a level of less than 5 mS/cm from the surface to 20 cm depth. The salts were distributed evenly throughout the columns after 200 - 400 mm leaching water had been added, indicating that leaching of salts was essentially completed.

Na, K, Ca and Mg also showed similar vertical distribution to that of electrical conductivity before leaching (Figs. 4.3 - 4.6); the content of which on the surface 5 cm ash were 36000 μg/g, 2200 μg/g, 2300 μg/g and 1400 μg/g respectively. With increasing leaching rate, these metals were displaced to greater depths and distributed evenly along the columns after 200 mm or more water was added. The rapid decrease in these metals would reflect a rapid dissolution of inorganic salts during the early stage of leaching. In the later stage of leaching after most of the inorganic salts have dissolved, slow dissolution of glassy siliceous fly ash matrix would become dominant (Dudas, 1981).

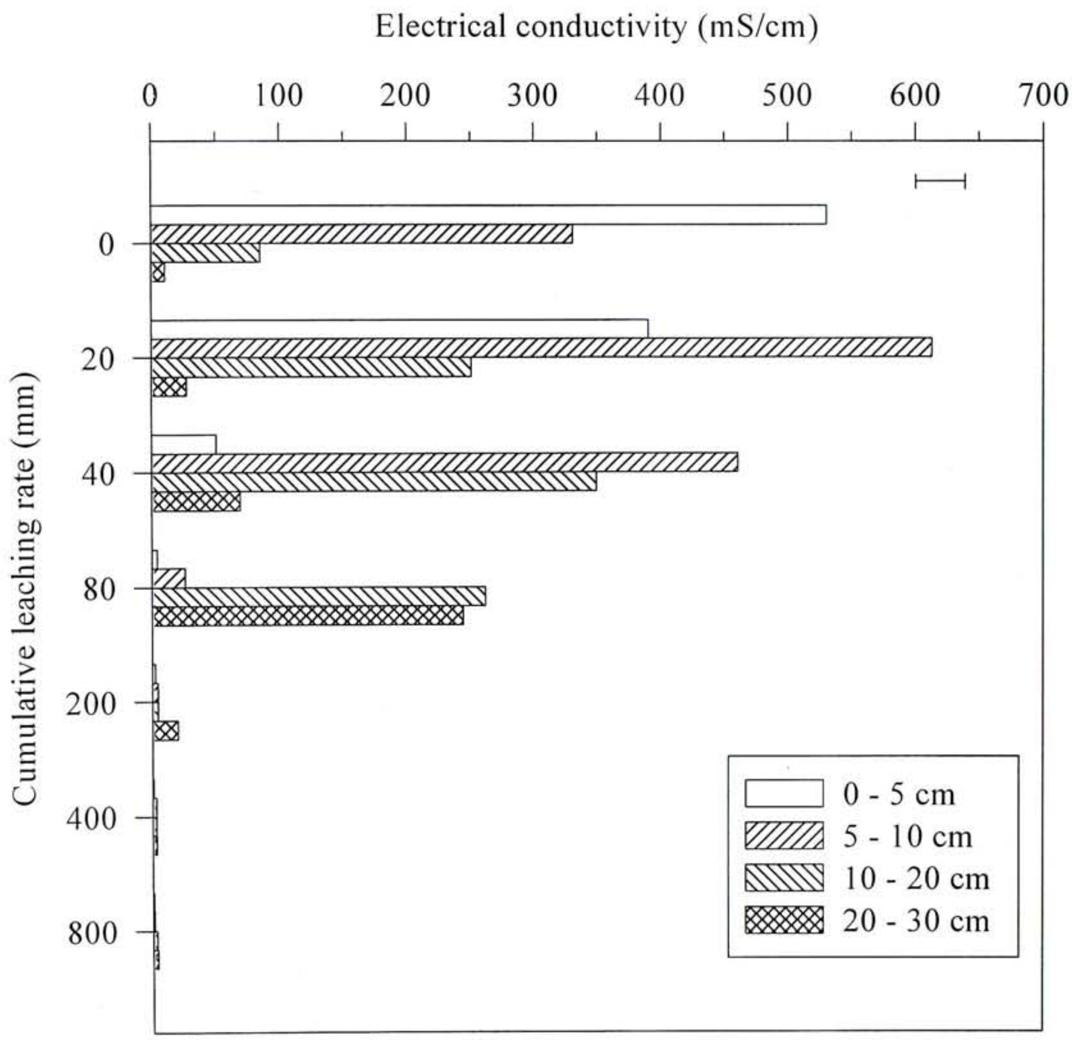

Fig. 4.2 Electrical conductivity of fly ash in columns after being leached by different amount of water (mm). Horizontal bar denotes LSD at $p<0.05$.

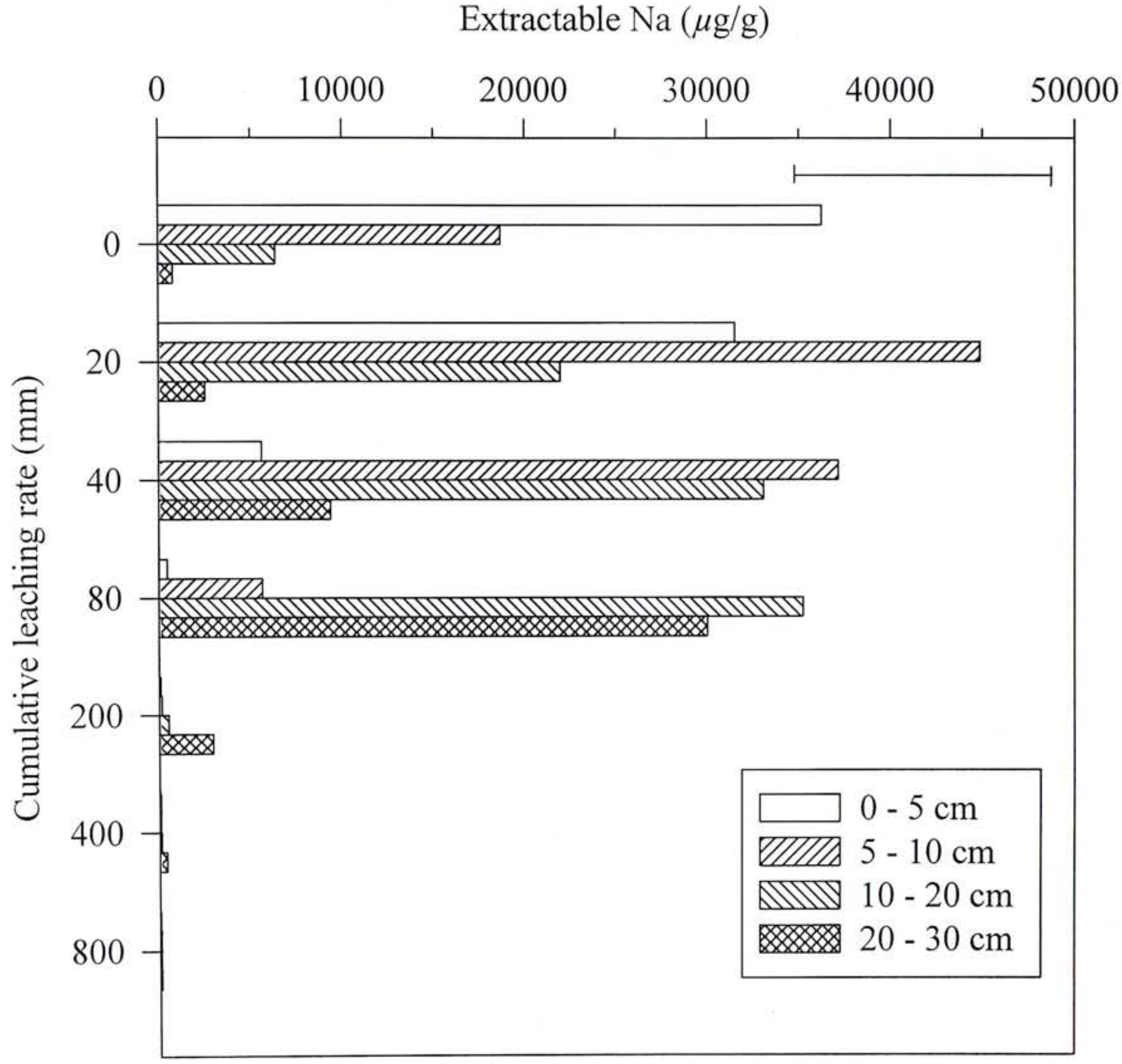

Fig. 4.3 Extractable sodium content of fly ash in columns after being leached by different amount of water (mm). Horizontal bar denotes LSD at $p<0.05$.

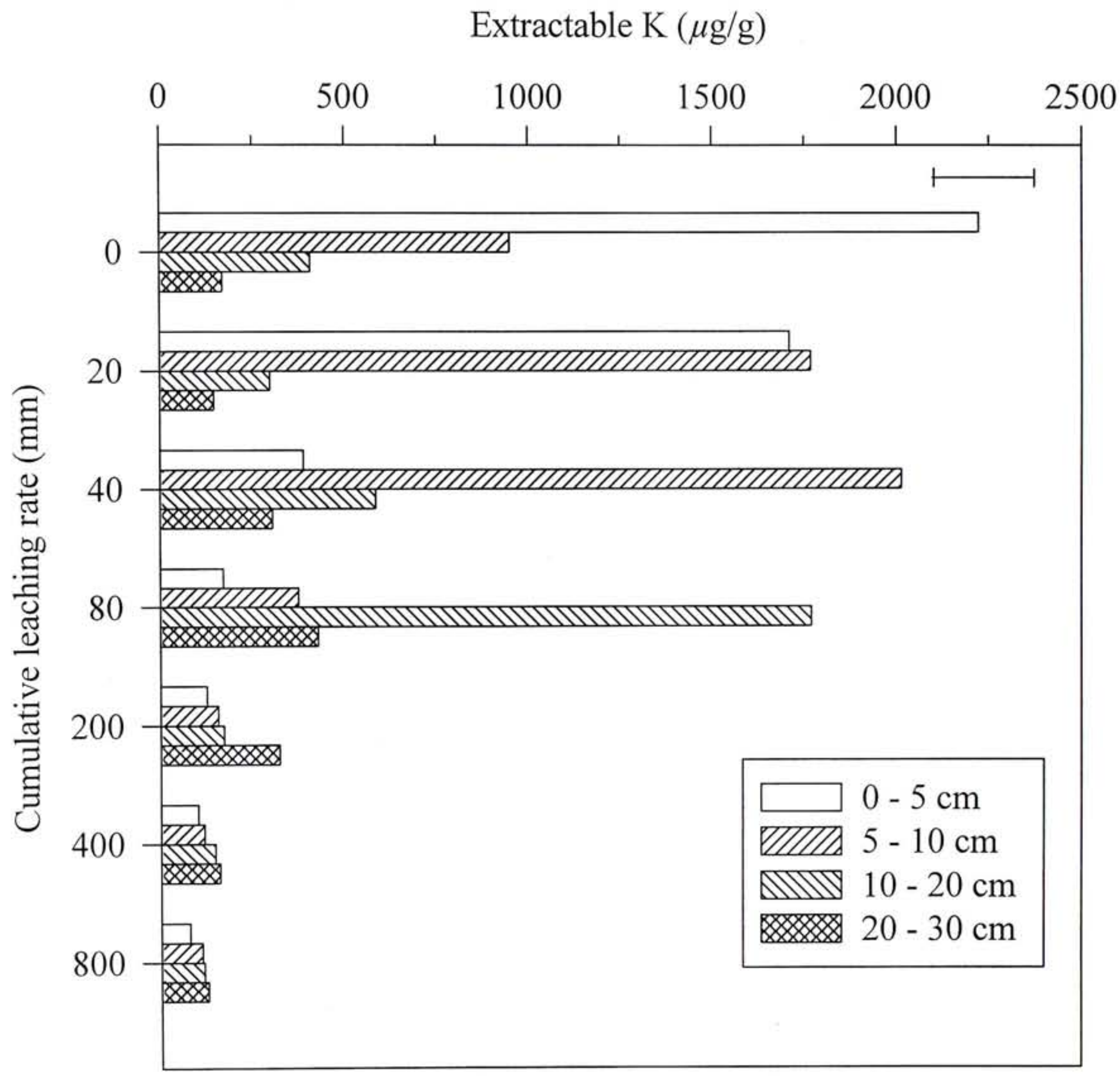

Fig. 4.4 Extractable potassium content of fly ash in columns after being leached by different amount of water (mm). Horizontal bar denotes LSD at $p<0.05$.

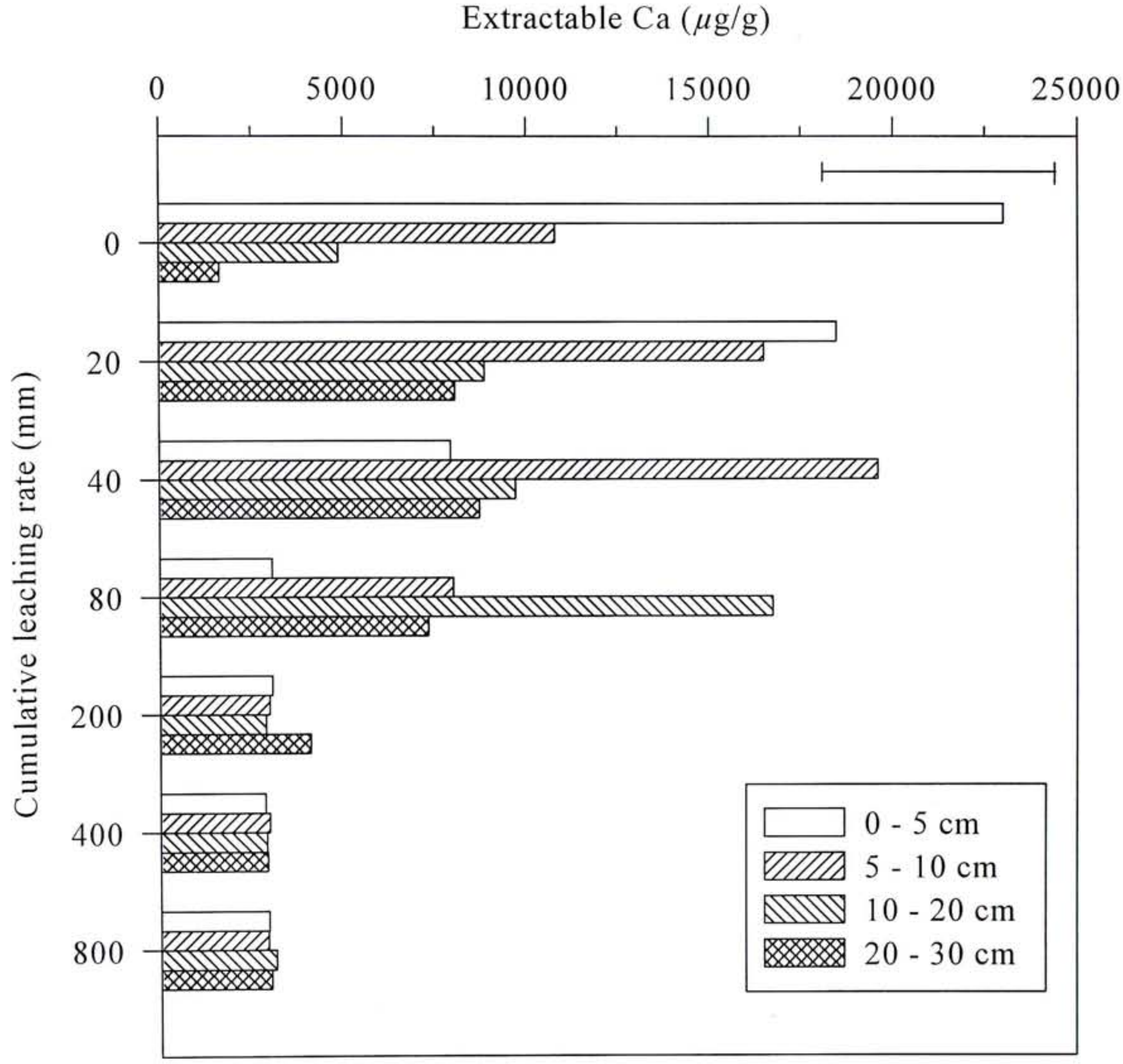

Fig. 4.5 Extractable calcium content of fly ash in columns after being leached by different amount of water (mm). Horizontal bar denotes LSD at $p<0.05$.

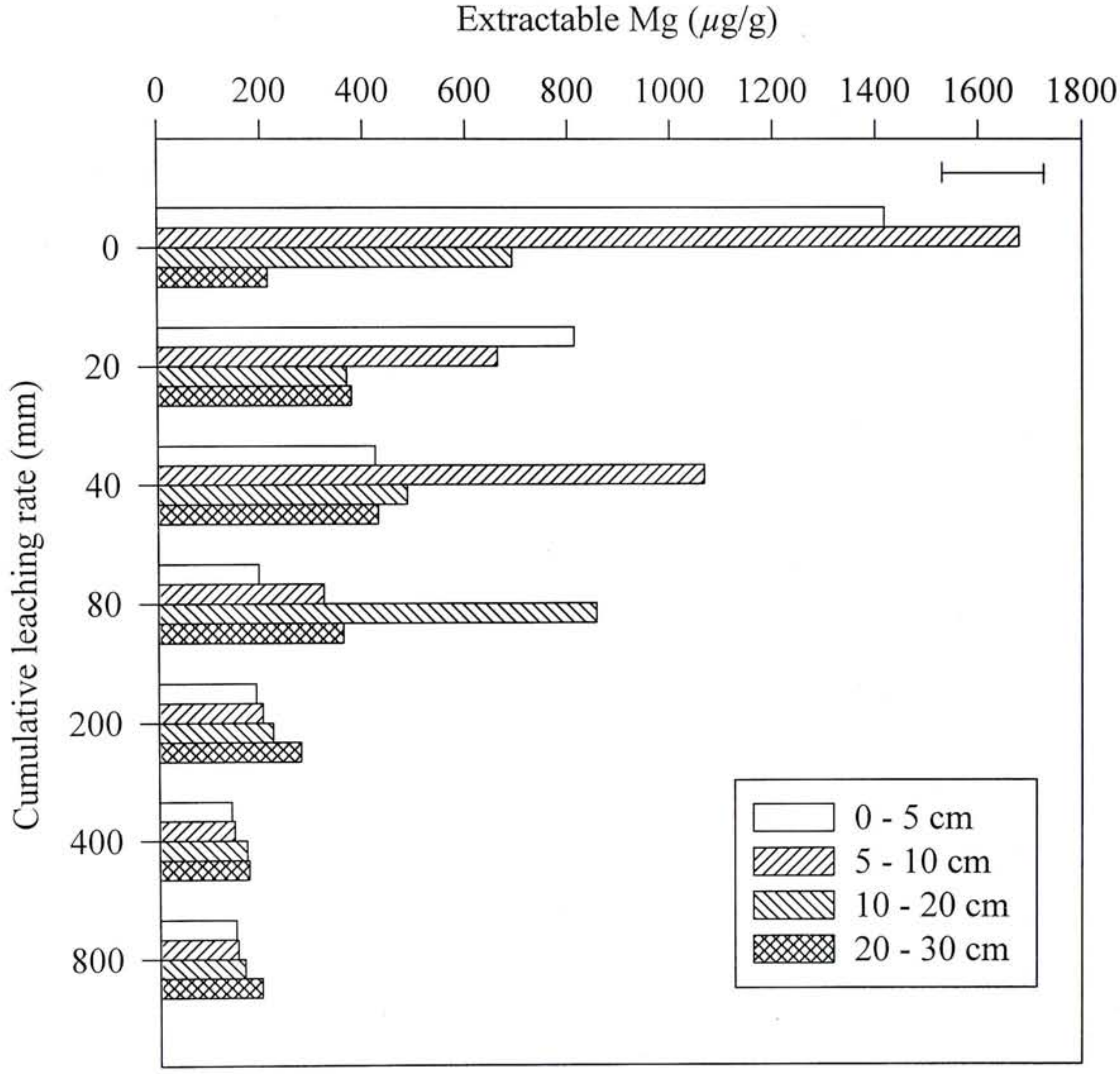

Fig. 4.6 Extractable magnesium content of fly ash in columns after being leached by different amount of water (mm). Horizontal bar denotes LSD at p<0.05.

The distribution of B in the ash profile is shown in Fig. 4.7. The initial B distribution was similar to those of salts, with the highest level on the ash surface (24 μg/g). With increasing leaching rate, B was displaced downwards (4 μg/g on the surface ash after leaching with 200 mm water leached) but had not levelled off along the vertical distribution, even at 800 mm of leaching water. Although the distribution of B was similar to that of salts, there was a difference in the effectiveness of leaching in removing these constituents from the ash.

The extent of leaching for salts (measured as electrical conductivity) and B expressed in terms of the percentage of remaining in the surface 5 cm ash, as related to amount of water leaching, is shown in Fig. 4.8. The slope of the curve at any given amount of water applied is a measure of the effectiveness. More than 90% of the extractable salts had been leached after 40 mm of water was added while B needed more than 200 mm of leaching water to attain this level. It is evident, by comparing the two curves, that salts was removed more efficiently than B.

The slower removal rate of B than salts by leaching of soil was reported in other studies on soil (Reeve *et al.*, 1955; Bingham *et al.*, 1972; Keren and Bingham, 1985). The salt content of a soil was reduced to less than 20% of the initial value with 30 cm of water for each 30 cm depth of soil considered, whereas 3 times more water was required for the same percentage reduction in boron (Keren and Bingham, 1985). Adsorption of B was considered to be a possible mechanism which controls B removal. Since fly ash contains substantial quantities of mullite (aluminosilicate) and

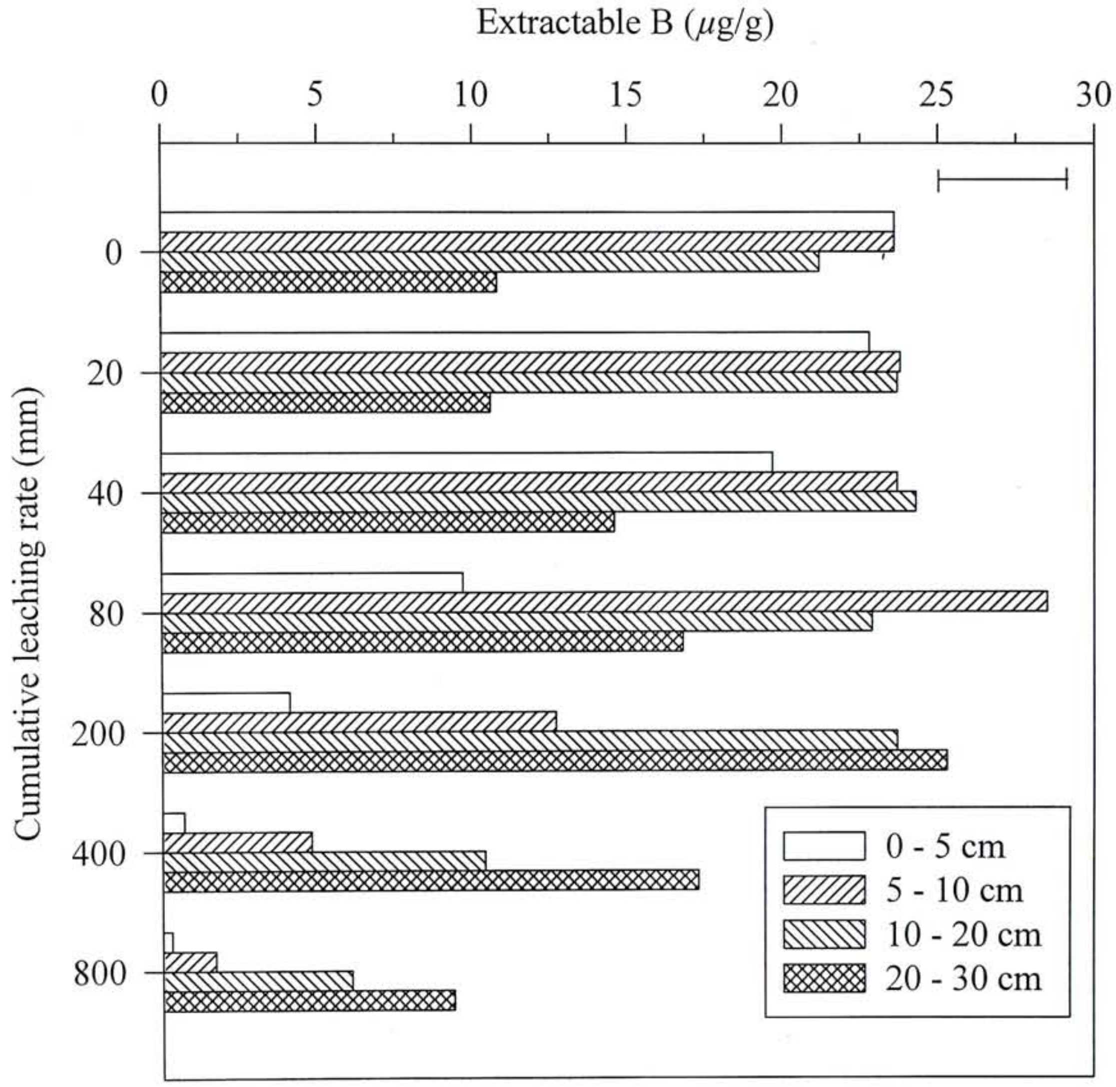

Fig. 4.7 Hot water extractable boron content of fly ash in columns after being leached by different amount of water (mm). Horizontal bar denotes LSD at $p<0.05$.

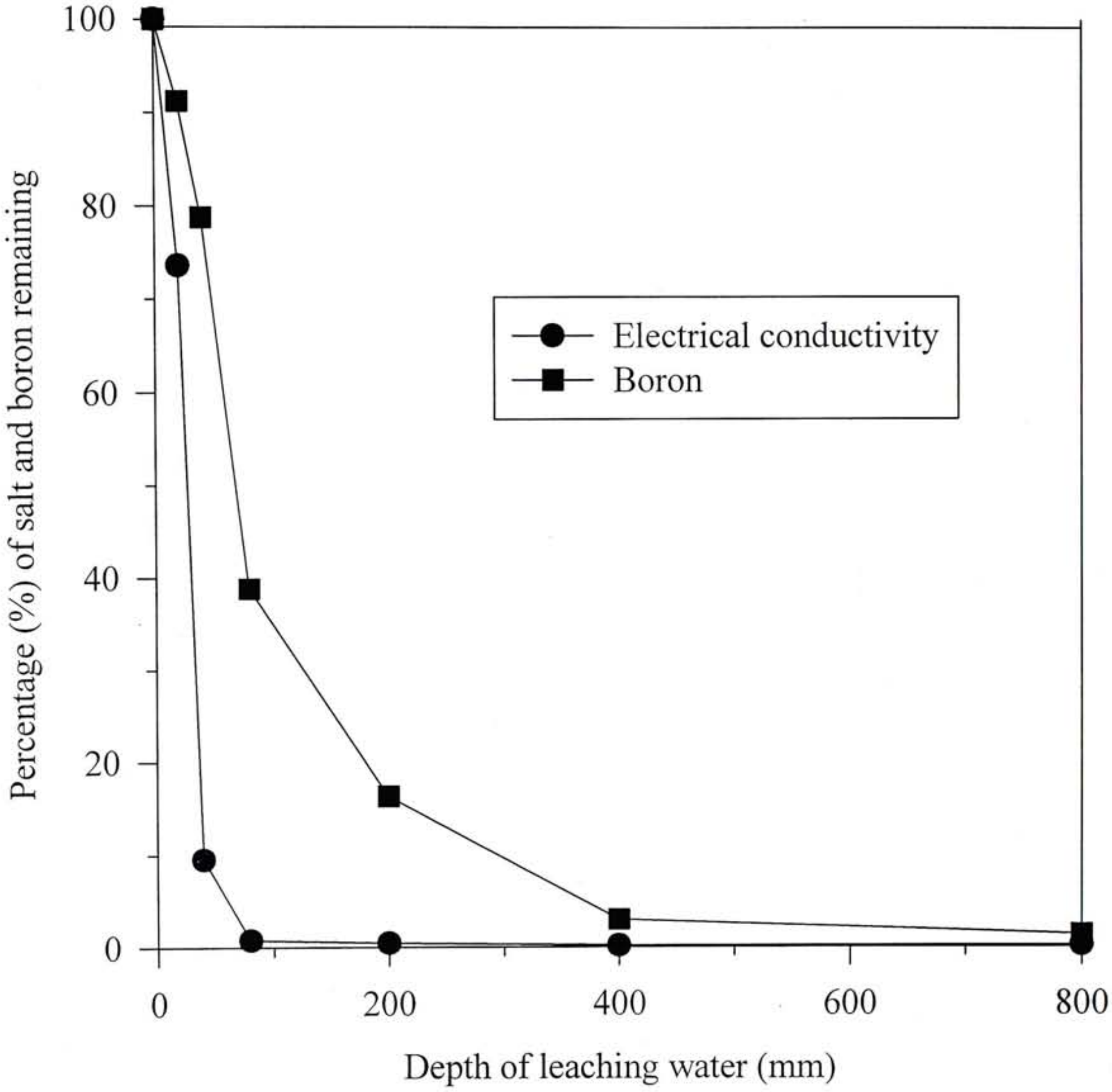

Fig. 4.8 Percentage of salt (measured as electrical conductivity) and hot water extractable boron remaining in the surface 5 cm in ash columns after being leached by different amount of water (mm).

ferric oxide minerals, the adsorption of B would result and the maximum sorption occurs in the pH range of 8 to 10 (Keren and Bingham, 1985). Moreover, B could be incorporated into $CaCO_3$ and precipitated as secondary mineral in alkaline soil environments (Hollis *et al.*, 1988). The presence of Ca in solution can enhance the adsorption by the formation of positively charged ion pair $CaB(OH)_4^+$ which has a much higher affinity for the negatively surface charge of oxide minerals under alkaline conditions than the borate anion (Mattigod *et al.*, 1985). Any B that remained in the ash was likely to be contained in the less soluble interior glassy matrix of the particles (Warren and Dudas, 1985), possibly in the form of borosilicates of limited solubility (Cox *et al.*, 1978).

The effect of leaching on pH of fly ash is shown in Fig. 4.9. Before leaching started, pH of the surface ash (0-5 cm) was the lowest (7.6) and gradually increased downward to the bottom 20-30 cm (pH 8.5). No obvious change in pH of the ash after 20 mm leaching water added. However the pH of the surface 5 cm increased profoundly to about 8.4 after 40 mm of leaching water was applied while the pH of the lower layers was reduced significantly. At higher leaching volume, the pH of the surface layer remained at 8.1-8.5 with slightly higher pH at the lower layers.

The change in pH of ash against the leaching rate was opposite to those of salts (Figs. 4.2 and 4.9). This could be due to the formation of bicarbonate ion when the salts (especially Na) were washed out, causing the pH value to increase to about 8.5 (Wood, 1995). Similar distribution and trend of pH and salts in the ash lagoon at Tsang Tsui occurred

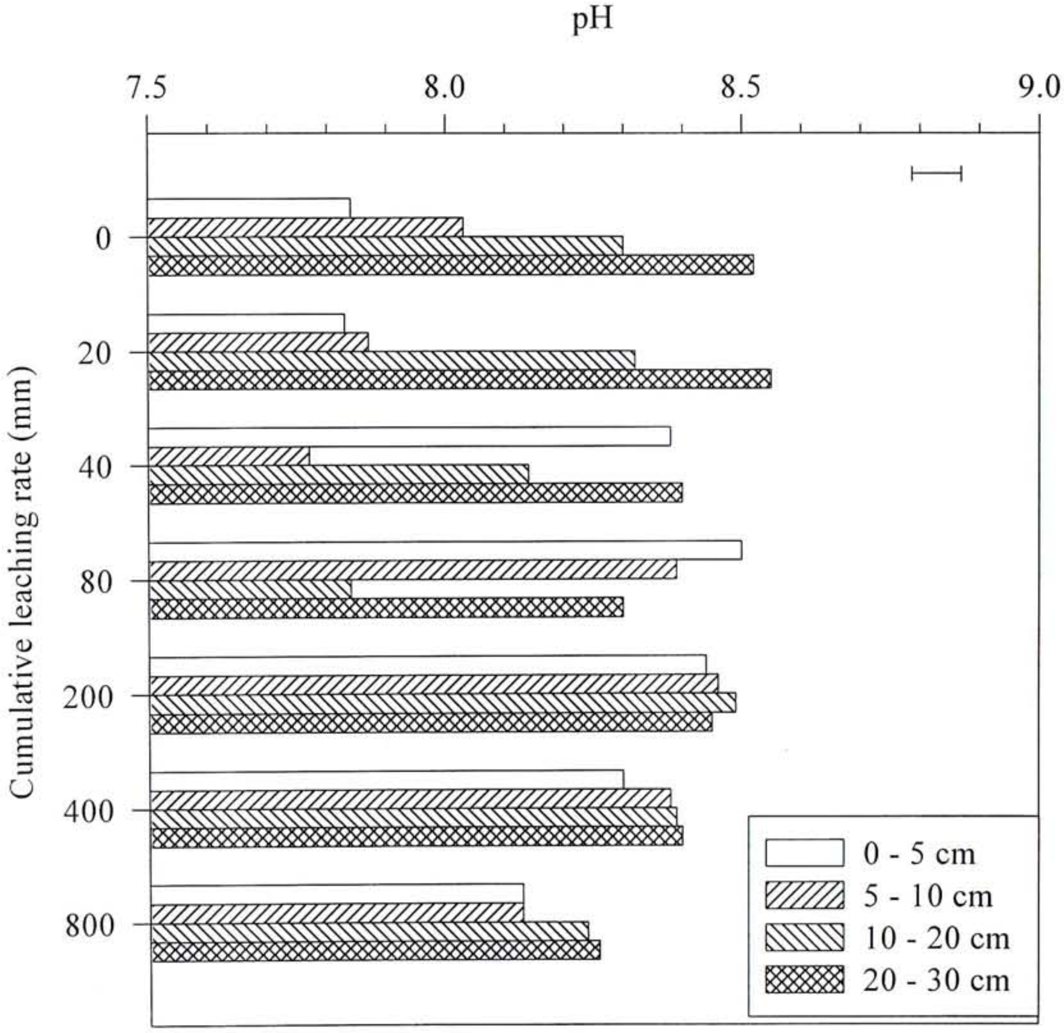

Fig. 4.9 pH fly ash in columns after being leached by different amount of water (mm). Horizontal bar denotes LSD at p<0.01.

that pH increased gradually from 8.1 at the ash surface to 8.6 at 60 cm depth while salts (measured as electrical conductivity) decreased from 112 to 63 mS/cm (Figs. 2.2 and 2.4). A similar trend was also observed in another study on ash spoils (Shaw, 1996). This is common in sodic soils (salts are composed mainly of Na) where the Na and high pH cause humic colloids to deflocculate and clays to swell or disperse, as the normal attractive forces become forces of repulsion, leading to an unstable soil structure (Wood, 1995). Whether leaching could affect the physical properties of ash needs further investigation. However, it seems that the Ca in fly ash is sufficient to replace Na to permit adequate permeability of ash.

4.3.2 **Plant growth on leached ashes**

Growth of ryegrass, *Lolium perenne*, was moribund on surface ash which had been leached by less than 80 mm of water (Fig. 4.10). At leaching rates greater than 80 mm, the dry weight of grass increased significantly as leaching increased, reaching a maximum yield (0.29 g dry matter/pot) at 400 - 800 mm leaching rate. A strong negative correlation was also obtained between the dry weight of ryegrass and electrical conductivity ($r=0.99$), B ($r=0.99$), K ($r=0.95$), Na ($r=0.94$), Mg ($r=0.90$) and Ca ($r=0.82$).

High salts and B were found to be the major limiting factors to plant growth in the present study. For most plants, growth is adversely affected at electrical conductivity values (measured in saturation extraction) $\geq$ 4 mS/cm (U.S. Salinity Laboratory Staff, 1954; Townsend and Gillham, 1975). Overall for plant growth, level

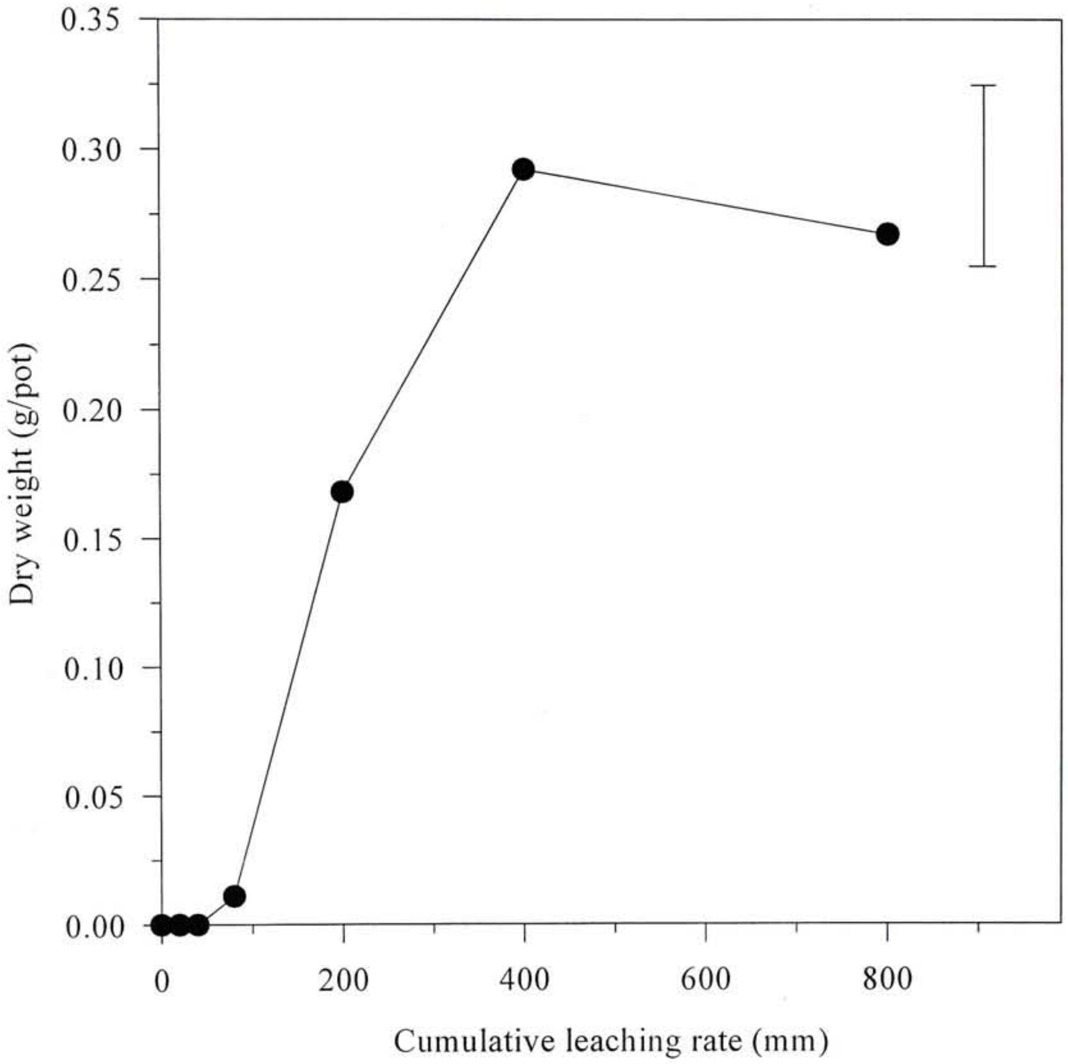

Fig. 4.10 Dry weight of *Lolium perenne* (grown for 90 days old) in the surface 5 cm ash after being leached by different amount of water. Vertical bar denotes LSD at $p<0.05$.

less than 4 μg/g B seem to be widely considered as non-toxic, 4-10 μg/g B slightly toxic, 11-20 μg/g B moderately toxic, 21-30 μg/g B toxic and > 30 μg/g B highly toxic (Hodgson and Townsend, 1973; Hodgson and Buckley, 1975). Growth of *Lolium perenne* was observed in ash after leaching with more than 80 mm water, with an electrical conductivity of 3.8 mS/cm and B concentration of 9.7 μg/g which are in a range of slightly toxic to plants. B toxicity symptoms including chlorosis and subsequent necrosis of leaf margin and tip were observed.

Leaching of fly ash under laboratory conditions significantly decreased the salt and B contents and consequently its toxicity to plants. In other studies of fly ash, reduction in the salt and B levels of fly ash by leaching was also obtained (Jones and Lewis, 1960; Phung *et al.*, 1979; Dudas, 1981; James, 1982; Aitken *et al.*, 1984; Warren and Dudas, 1988; Jones, 1995; Kukier and Sumner, 1996). Salts and B leached rapidly from fly ash amended soil (Phung *et al.*, 1979; Adriano *et al.*, 1982; Ghodrati, *et al.*, 1995). Plant growth restrictions were relieved as the contents of salts and B were reduced (Jones and Lewis, 1960; Collier and Greenwood, 1977).

Leaching of fly ash under field conditions significantly decreased the salt and B contents and its phytotoxicity (Jones and Lewis, 1960; Townsend and Gillham, 1975) as well as increased the abundance of microorganisms and microbial activity (Klubek *et al.*, 1992). Lagooning, stockpiling and leaching considerably reduced the detrimental effects of soluble salts and B content associated with fly ash (Townsend and Hodgson, 1973). In the present leaching study, irrigating ash with 800 mm of water, which is about one third the average annual rainfall (about 2300 mm) in Hong Kong for the last ten years (Royal Observatory, 1996), could reduce the salt and B contents remarkably. However, the levels of salts and B in the fly ash collected from the lagoon at Tsang Tsui, which had been settled for about three years, were still very high (Table 2.2) as compared to ashes in the lagoon from previous studies (Lam, 1991; Lou, 1991). Although extrapolating laboratory results precisely to field conditions would be difficult (Dodd *et al.*, 1981), this discrepancy between the laboratory and field results could be explained by the poor drainage of the fly ash lagoon *in situ* which impedes the downward flux of water. The underlying strata of the lagoon are marine mud and alluvial deposits on top of decomposed granite. A grout-filled, geo-textile mattress was inclused on the outer seawalls of the lagoon to reduce the permeation of the decantrate via the normal rubble structure to the sea (Ashton, 1991). In summer when rainfall attained several hundred mm a month, the waterlogged nature of the fly ash lagoon could be shown easily by flooding. As a result, the actual leaching fraction (amount of water pass through ash carrying out salts) by rainfall would be limited. In a lagoon located in semi-arid regions of Zimbabwe where the rainfall was low and temperature was high, the problems of surface accumulation of salts and B (due to high evaporation rate and covered ash dam wall) might be expected to last much longer and would pose a severe problem for natural seed establishment on uncovered ash (Piha *et al.*, 1995).

Since the rate of decrease in soluble constituents in areas with a high water table and/or impeded drainage may well be considerably lower (Jones and Lewis,

1960) drainage constructions (namely deep ditch, tile and drainage well) should be installed before effective leaching commenced so as to allow the irrigation water to percolate through the rootzone and keep the water table sufficiently deep to prevent the flow of salt-laden groundwater up to the rootzone by capillary forces (Rhoades, 1982; Fuller and Warrick, 1985). With the aid of the drainage system coupled by natural weathering and irrigation, soluble salts and B would be diminished with time. Once these plant growth limiting factors are removed, natural colonization and vegetative production on ash lagoon would be faster and plant failure might be reduced.

4.4 **CONCLUSIONS**

The column study demonstrates that soluble salts and B, which are probably the major limiting factors to vegetation establishment in lagooned fly ash, could be effectively removed by leaching. Dry yield of ryegrass increased as the salt and B contents in ash were reduced by leaching. This suggests that prolonged leaching, preferably coupled with good drainage could enhance the revegetation of fly ash lagoons.

Chapter 5 **EFFECTS OF ORGANIC AMENDMENTS ON PLANT GROWTH ON PRE-LEACHED FLY ASH**

5.1 **INTRODUCTION**

Deficiency of organic matter and major plant nutrients is common on wastelands including fly ash lagoons. An immediate and effective method to remedy this problem is by applying fairly substantial amounts of chemical fertilizers. However, growth can decrease rapidly after treatment on some wastelands. Further fertilizer additions relieve the problem only temporarily, showing that nutrient deficiency is fundamental (Bloomfield *et al.*, 1982).

The predominant requirement for primary production in different ecosystems is N (Bradshaw, 1983). Most of the N in soil is held in organic form. N supply to plants depends on the slow but continuous breakdown of organic matter, releasing the N by mineralisation. The total N capital required so as to provide the annual requirement of 100 kg N/ha (decomposition rate of about 1/16) is about 1600 kg N/ha in temperate ecosystems (Bradshaw, 1983). In tropical ecosystems, the total N capital might be lower due to higher decomposition rate.

Successive fertilization to accumulate the required level of N capital is possible but expensive. A well-established alternative is to incorporate legumes in the vegetation, which had been reported to accumulate at least 100 kg N/ha/year (Dancer *et al.*, 1977; Jefferies *et al.*, 1981). Of the five most promising tree species selected in lagooned fly ash, two of them are N-fixing trees which would be helpful in N build-up on ash lagoons (see Chapter 3). However, limitations in using N-fixing species are (1) long time for N accumulation, (2) difficulty in obtaining salt-tolerant species and (3) nutrient requirement of the legumes.

Addition of N-rich organic materials such as sewage sludge is a low cost alternative. A single large application of sewage sludge is very effective; 50 tonnes dry solids per ha will provide 1500 kg N/ha in organic form. C/N ratios in sludge normally fall well below the threshold of 25 above which N supply may limit decomposition. The N must be released by mineralisation to become available to plants. Other nutrients like P in organic materials could also improve plant growth on wasteland since P may be complexed and rendered unavailable in wasteland substrates.

Organic amendments are important for successful reclamation of many different sites where the starting materials are low in nutrients and have poor physical characteristics. Many studies have shown that amending minespoils with organic materials could improve not only long-term fertility but also physical conditions and microbial activity (Stroo and Jencks, 1985; Seaker and Sopper, 1988a and b). Sewage sludge additions to minespoils resulted in significant increases in above-ground biomass and canopy (Topper and Sabey, 1986; Pietz *et al.*, 1989). In an incubation experiment, plant nutrients (N and P), microbial activity, dehydrogenase activity and microbial population were increased by addition of sludge and pig manure compost to lagooned fly ash (Chu, 1992). Coal refuse disposal sites have also been revegetated by the application of sewage sludge without the use of soil cover (Joost *et al.*, 1987). The objective of the present study was to examine the effects of organic wastes, including sewage sludge, pig manure compost, horse manure compost and spent mushroom compost, on plant growth and elemental uptake on fly ash. Since there was no plant growth on lagooned ash alone (as shown in Chapter 3) probably due to the high soluble salts and B content in ash, the lagooned ash used for the following experiment had been leached by water in the pots before planting started.

5.2 MATERIALS AND METHODS

5.2.1 Collection of materials

Fly ash was collected from the surface (0-15 cm) of the middle lagoon at Tsang Tsui in April 1995. A garden soil comparing the effect on plant performance was obtained from a nursery in the campus of The Chinese University of Hong Kong. The lagooned fly ash and garden soil were sieved through an 1 cm mesh sieve to remove gravel and debris. All the organic amendments were collected locally; sewage sludge was collected from Shek Wu Hui sewage treatment plant; pig manure compost was collected from Sha Ling composting plant. Horse manure compost and spent mushroom compost were obtained from a commercial composting plant at Ngau Tam Mei and a mushroom farm at Sheung Shui respectively.

5.2.2 Chemical analysis of potting media

The properties of the various materials were determined after air drying and grinding to pass through a 2 mm sieve. The samples were analyzed for the following properties: pH (pH meter, sample : 0.01 M $CaCl_2$ = 1:2.5 (w:v)); electrical conductivity (conductivity meter, in saturation extract); organic C (Walkley and Black, 1934); total and extractable N (colorimetric method with a Lachat QuickChem AE Automated Ion Analyzer after salicylic acid modification of Kjeldahl digestion and extraction with 1 M potassium chloride, respectively); total and extractable P (molybdenum blue method with Lachat QuickChem AE Automated Ion Analyzer after salicylic acid modification of Kjeldahl digestion and extraction with 0.5 M sodium bicarbonate at pH 8.5, respectively); total and extractable K, Ca, Mg, Na, Cu, Zn, Pb and Cd (Hitachi Z8100 Polarized Zeeman atomic absorption spectrophotometry after nitric acid-sulphuric acid (5:1) digestion and 1 M neutral ammonium acetate extraction, respectively); and total and hot water extractable B (inductively coupled plasma-atomic emission spectrometry (ICP-AES) after nitric acid-sulphuric acid (5:1) digestion and azomethine-H method with Lachat QuickChem AE Automated Ion Analyzer, respectively).

5.2.3 **Plant growth experiment**

Fly ash was firstly filled in pots (height 9 cm; diameter 10 cm). After presaturation by introducing distilled water from the bottom, the ash was allowed to equilibrate for one week. Leaching was then initiated by adding distilled water slowly to each pot at rate of 200 mm in terms of cumulative volume. The leached fly ash was then mixed with organic wastes (sewage sludge, SS; pig manure compost, PMC; horse manure compost, HMC and spent mushroom compost, SMC) at rates equivalent to 50 and 100 tonnes/ha. Peatmoss (P) from a horticultural supplier was mixed with the leached fly ash at a rate equivalent to 50 tonnes/ha and chemical fertilizer (Nitrophoska: N, 15%; P_2O_5, 9% and K_2O, 15%) at a rate of 2 tonnes/ha for comparison. A garden soil was also included for the comparison as well as leached ash alone as control.

Seeds of *Lolium perenne* were germinated in perlite and 20, one week old seedlings were transplanted to each pot which had been equilibrated for one week. The pots were arranged in randomized blocks in a greenhouse. All treatments were replicated three times and were irrigated daily with tap water (Plate 5.1). The pots were harvested after 60 days. The shoots and roots were washed with tap water for one times followed by distilled water for two times and then oven dried at 60°C for one week to determine their dry weight. Nutrients (N and P) and metals (B, Cu, Zn, Pb and Cd) contents in shoots, which had been ground using a stainless steel electric mill with 1 mm sieve, were determined using methods as described above.

5.2.4 **Statistical analysis**

Untransformed data of plant growth were subjected to one way analysis of variance (ANOVA) at the 0.05 significance level to test the difference among various treatments. Least significant difference (LSD) for the means was calculated where necessary at the 0.05 significance level. All statistical analyses were performed by means of SPSS for Windows Release 6.0 (SPSS, 1989).

5.3 **RESULTS AND DISCUSSION**

5.3.1 **Chemical properties**

Plate 5.1 Pot trial with *Lolium perenne* in a greenhouse.

Table 5.1 shows the chemical properties of the organic wastes, leached ash and soil. Sewage sludge, horse manure compost and peat moss were acidic. Pig manure compost and spent mushroom compost were slightly alkaline. After leaching, fly ash was also alkaline (pH=8.4) and the electrical conductivity was reduced to 2.7 mS/cm, indicating that soluble salts were leached away to level suitable for plant growth by about 200 mm of leaching water which was consistent with the findings shown in Chapter 4. Among the organic wastes, electrical conductivity was the highest in pig manure compost (26.6 mS/cm), followed by sewage sludge (17.7 mS/cm) and spent mushroom compost (13.6 mS/cm). The electrical conductivity in horse manure compost was relatively lower (2.9 mS/cm). High salt problems would occur in plants growing on waste-amended fly ash.

The C/N ratios of organic materials were below 10 (with the lowest of 3 for sewage sludge) except horse manure compost. High organic C content in horse manure compost (50.7%) as compared to other organic wastes (30-40%) coupled with relatively lower N content (1.37%) resulted in a C/N ratio of 37 which was the highest among the organic wastes. Sewage sludge contained high concentrations of total N (9.93%) and ammonium-N (4230 μg/g) but its concentration of nitrate-N (4.92 μg/g) was lower than those of pig manure compost (287 μg/g) and horse manure compost (10.9 μg/g). On the other hand, pig manure compost contained higher concentrations of total P (1.63%) and extractable P (1700 μg/g) than the other organic wastes. In general, the contents of C, N and P for the organic wastes were higher than that of soil and leached fly ash by an order of about 10 to 100.

Table 5.1 Chemical properties of the materials used in the experiment.

	SS	PMC	HMC	SMC	P	S	Ash
pH	6.3 (0.1)	7.3 (0.1)	5.8 (0.0)	7.5 (0.2)	2.7 (0.1)	6.4 (0.0)	8.4 (0.0)
EC (mS/cm)	17.7 (0.5)	26.6 (0.4)	2.9 (0.0)	13.6 (0.5)	1.5 (0.0)	0.2 (0.0)	2.7 (0.5)
Organic C (%)	32.2 (1.1)	36.1 (2.0)	50.7 (1.3)	40.7 (0.3)	54.7 (0.8)	2.81 (0.16)	0.54 (0.16)
Total N (%)	9.93 (0.17)	4.25 (0.03)	1.37 (0.03)	4.50 (0.02)	0.92 (0.10)	0.22 (0.01)	0.09 (0.03)
C/N	3.24	8.49	37.0	9.04	59.5	12.8	6.00
Ext NH_4^+-N (μg/g)	4230 (40)	1530 (50)	76.3 (2.4)	121 (3)	161 (8)	5.2 (0.1)	0.1 (0.1)
Ext NO_3^--N (μg/g)	4.92 (0.29)	287 (25)	10.9 (0.6)	0.55 (0.28)	0.59 (0.00)	29.2 (0.2)	0.75 (0.03)
Total P (%)	1.11 (0.09)	1.63 (0.28)	0.10 (0.01)	0.37 (0.00)	0.01 (0.00)	0.04 (0.00)	0.28 (0.01)
Ext PO_4^{3-}-P (μg/g)	1110 (0)	1700 (130)	468 (14)	1410 (200)	15 (2)	110 (4)	12 (3)

Standard deviations of the mean are parenthesized.

The high soluble salt content of organic wastes was reflected by the high concentrations of Na, K, Ca and Mg as shown in Table 5.2. Pig manure compost contained comparatively higher extractable Na, K and Mg than other wastes. Spent mushroom compost had the highest extractable Ca content possibly due to its high lime content. As compared to organic wastes, the extractable Na, K, Ca and Mg contents in leached fly ash were low as a result of leaching. Although the total B concentrations of organic wastes were lower than that of leached fly ash (184 μg/g), their extractable B contents were higher than that of fly ash (5.2 μg/g), suggesting that B toxicity of plant would be a problem when growing in organic amended ash. However, most of the B in fly ash would be in the less soluble interior glassy matrix of the particles (Warren and Dudas, 1985). As for the other elements, sewage sludge contained high concentrations of Cu (total 685 μg/g; extractable 10.8 μg/g) and Zn (total 1130 μg/g; extractable 215 μg/g) in ranges usually found in sewage sludge (Mininni and Santori, 1987). The corresponding Cu and Zn concentrations of pig manure compost ranked the second since Cu is added to pig and poultry feeds as a growth stimulant and zinc is also added in high levels to balance the high amount of copper (Chaney, 1973). Pb and Cd contents in all organic wastes, soil and ash were not detectable.

The amounts of Cu and Zn applied to fly ash along with organic materials were calculated showing that the amounts of Cu and Zn were well below the recommended lifetime limits for Cu (280 kg/ha) and Zn (560 kg/ha) (USEPA, 1977).

Table 5.2 Metal content of materials used in the experiment.

	SS	PMC	HMC	SMC	P	S	Leached ash
Total Na (%)	0.09 (0.02)	0.36 (0.02)	0.08 (0.02)	0.08 (0.02)	0.07 (0.01)	0.03 (0.01)	0.07 (0.02)
Ext Na (μg /g)	616 (23)	4110 (1080)	435 (50)	562 (120)	392 (59)	39 (14)	148 (7)
Total K (%)	0.17 (0.01)	1.13 (1.30)	0.21 (0.00)	0.82 (0.85)	0.01 (0.01)	0.37 (0.03)	0.09 (0.00)
Ext K (μg /g)	755 (62)	22900 (200)	2460 (150)	14300 (500)	103 (63)	105 (4)	115 (3)
Total Ca (%)	0.48 (0.05)	0.15 (0.05)	0.43 (0.01)	0.11 (0.06)	nd#	0.27 (0.00)	0.07 (0.00)
Ext Ca (μg /g)	5480 (1280)	4160 (1830)	4480 (3900)	5980 (30)	1140 (270)	3340 (1920)	792 (27)
Total Mg (%)	0.25 (0.04)	0.88 (0.05)	0.06 (0.04)	0.57 (0.02)	nd	0.01 (0.00)	0.62 (0.05)
Ext Mg (μg /g)	1010 (80)	2910 (580)	647 (20)	3500 (1480)	355 (472)	88.1 (34.2)	86.0 (3.0)
Total B (μg /g)	78.4 (1.8)	108 (30)	22.8 (32.0)	32.0 (3)	66.2 (13.9)	51.6 (8.1)	184 (7.8)
Ext B (μg /g)	4.0 (5.7)	33.6 (24.1)	15.6 (13.7)	107 (11)	4.7 (6.0)	0.4 (0.0)	5.2 (0.7)
Total Cu (μg /g)	685 (8)	215 (3)	9.6 (0.5)	13.4 (3.2)	nd	9.9 (0.9)	32.5 (1.6)
Ext Cu (μg /g)	10.8 (1.1)	nd	nd	nd	nd	0.1 (0.1)	nd
Total Zn (μg /g)	1130 (452)	630 (56)	107 (79)	252 (16)	11.5 (1.5)	115 (18)	70.0 (4.0)
Ext Zn (μg /g)	215 (18)	1.0 (0.6)	nd	0.6 (0.8)	nd	0.4 (0.7)	nd
Total Pb (μg /g)	nd	nd	nd	nd	nd	nd	nd
Ext Pb (μg /g)	nd	nd	nd	nd	nd	nd	nd
Total Cd (μg /g)	nd	nd	nd	nd	nd	nd	nd
Ext Cd (μg /g)	nd	nd	nd	nd	nd	nd	nd

Standard deviations of the mean are parenthesized.
#nd represents not detectable.

5.3.2 **Plant growth on ash amended with organic wastes**

Table 5.3 gives the dry weight yield of *Lolium perenne* with shoot, root and total dry weights. Application of organic wastes to leached ash resulted in lower total dry weight than soil (7.37 g/pot) and 50 tonnes/ha peatmoss (6.37 g/pot), but higher total dry weight than ash alone (0.67 g/pot) except 50 HMC, 100 HMC and 100 SS. Although there are some plant growth inhibiting factors in various organic wastes, their application to leached fly ash could enhance plant growth, to various extents, probably by the improvement of physical properties, nutrient status and microbial activities (Seaker and Sopper, 1988a and b). Improvements in plant establishment and microbial population on coal combustion ash by adding organic wastes have been reported (Rippon and Wood, 1975; Schwab *et al.* 1991).

To identify precisely the plant growth inhibiting factors would require further investigation but the adverse effects of horse manure compost at rates of 50 or 100 tonnes/ha) and sewage sludge (100 tonnes/ha) would probably be attributed to toxic substance(s) such as ammonia and ethylene oxide (Wong *et al.*, 1983) and the high C/N ratio in horse manure compost. Toxicity of compost usually depends on degree of maturity (Wong, 1985; Wong and Chu, 1985). Generally, a C/N ratio exceeding 25 would lead to immobilisation of N and reduction of available N for plant growth (Lanning and Williams, 1981). Fertilizer application could decrease the C/N ratio, and hence organic N mineralisation would increase (Parnas, 1975).

Table 5.3 Dry weight and shoot-root ratio of *Lolium perenne* under different treatments.

Treatment	*Lolium perenne* (g dry wt/pot)			Shoot/ Root Ratio
	Shoot	Root	Total	
C	0.26	0.40	0.67	0.66
50 SS*	1.80	0.41	2.20	4.42
50 PMC	1.47	1.42	2.89	1.04
50 HMC	0.06	0.09	0.15	0.65
50 SMC	0.70	1.13	1.84	0.62
100 SS	0.21	< 0.01	0.21	150
100 PMC	1.42	0.41	1.83	3.42
100 HMC	0.04	0.06	0.10	0.67
100 SMC	1.07	3.72	4.79	0.29
50 P	1.77	5.00	6.77	0.35
S	1.75	5.62	7.37	0.31
LSD ($p < 0.05$)	0.34	0.86	0.93	

* 50 SS, 50 PMC, 50 HMC, 50 SMC, 100 SS, 100 PMC, 100 HMC and 100 SMC represent fly ash mixed with 50 t/ha and 100 t/ha sewage sludge, pig manure compost, horse manure compost and spent mushroom compost respectively collected from particular locations as stated in text. C, 50 P and S denote control (fly ash alone), fly ash mixed with 50 t/ha peat moss and soil only respectively.

Dry weight reduction of *Lolium perenne* in higher rate sludge addition, from 2.20 g/pot (50 SS) to 0.21 g/pot (100 SS), would be due to toxicity by accumulation of soluble salts and ammonium ion. Moreover, the effects of phytotoxic elements including Zn, Cu and B in sewage sludge are well documented (Wong *et al.*, 1983; Mininni and Santori, 1987). A significant reduction of dry weight was also obtained in pig manure compost from 2.89 g/pot (50 PMC) to 1.83 g/pot (100 PMC). However, a remarkable increase in total dry weight was observed (from 1.84 g/pot to 4.79 g/pot) by increasing the application rate of spent mushroom compost (from 50 to 100 tonnes/ha) which is more innocuous.

5.3.3 **Plant elemental uptake**

Table 5.4 shows the concentrations of the plant nutrients (N and P) and trace metals (B, Cu and Zn) in the leaf tissues of *Lolium perenne*. There were no significant differences ($p>0.05$) between the control (ash alone) and the ash treated with horse manure compost or spent mushroom compost (50 and 100 tonnes/ha), but significantly higher concentrations of N were found in plants from sewage sludge or pig manure compost amended ash. Increase in N concentration in shoots was observed when higher rates of sewage sludge and pig manure compost were applied. Increase N and P contents in waste amended ash and plants was also reported in a field trial (Rippon and Wood, 1975). Higher N content in plants grown on spent mushroom compost were also noted, albeit the increases were not significant. Lower N content of plants in 100 HMC treatment was observed as reflected by the poorer growth (Table 5.3).

Table 5.4 Elemental contents[‡] of shoot tissue of *Lolium perenne* under different treatments.

	N	P	B	Cu	Zn
	(%)		(μg /g)		
50 SS*	3.77	0.34	530	10.8	119
50 PMC	2.04	0.16	422	1.43	21.9
50 HMC	1.05	0.17	1150	nd[#]	nd
50 SMC	1.61	0.28	523	3.02	12.5
100 SS	4.08	0.46	973	6.56	47.8
100 PMC	3.16	0.20	228	4.12	87.1
100 HMC	0.79	0.16	562	nd	nd
100 SMC	1.70	0.26	116	4.25	18.4
C	1.33	0.15	776	2.48	5.2
50 P	1.49	0.20	289	2.51	4.1
S	1.39	0.37	2	6.33	55.2
LSD ($p < 0.05$)	0.4	0.06	13	0.40	0.6

* See Table 5.3 for abbreviation of treatments.

[#]nd represents not detectable.

[‡] Pb and Cd contents were not detectable in shoots and not shown in table.

The foliar N contents of plants from the fly ash control (1.3%) were comparable to those from soil and 50 P (Table 5.4) while total dry weight was lower than that in soil and 50 P. It is suggested that approximately 1.3% of N is close to the minimal foliar N content to maintain a healthy and normal growth for *Lolium perenne*. Further increase in N supply by addition of organic amendments could stimulate dry matter production.

Foliar P was generally higher in plants grown on sewage sludge or spent mushroom compost as compared with the unamended ash control (Table 5.4). As for N, P concentration from sludge-grown plants increased from 0.34% to 0.46% as the sludge application rate doubled. However, the foliar P contents were comparable to those of plants grown on soil, which was different from that for N uptake. The lower P uptake in unamended and amended ash was presumably due to the unavailability of P as a result of the complexation with Al, Fe and Ca in ash (Townsend and Hodgson, 1973; Bradshaw and Chadwick, 1980).

All the plants grown in pots containing ash had higher foliar B concentrations than those in soil (Table 5.4). Phytotoxicity symptoms were observed for all plants by showing leaf tip necrosis which could be partly attributed to B toxicity. Those grown on 50 HMC (1150 μg/g) and 100 SS (973 μg/g) contained higher foliar B contents than unamended ash (776 μg/g). B concentrations greater than 300 μg/g dry weight in leaf indicate that B toxicity may be present (Nable *et al.*, 1997); leaf concentrations of B may exceed 700 to 1000 μg/g dry weight in extreme conditions of B toxicity. Pots containing ash mixed with various organic wastes had a relatively lower dry weight yield than soil (Table 5.3) which might be attributable to the inhibitory effect of the high B contents (Rippon and Wood, 1975). Adding ash-sludge mixture to soil in pots resulted in a reduction of shoot dry weight when compared with lower application rates and the poorer growth has been attributed to B toxicity (Kukier *et al.*, 1994; Wong *et al.*, 1996).

Foliar Cu contents in plants grown on amended ash were generally higher than those on unamended ash (2.48 μg/g), except 50 PMC, 50 HMC and 100 HMC, but the contents were comparable to those grown on soil. The foliar Cu contents of all the amended pots were far below the suggested tolerance level of Cu (level which are not phytotoxic but could result in decrease in growth) (Melsted, 1973).

As for Cu, foliar Zn contents of plants grown on amended ash were generally higher than that of unamended ash. The highest foliar Zn content was observed in 50 SS (119 μg/g) which is still below the suggested tolerance level (300 μg/g) (Melsted, 1973). Foliar Pb and Cd contents, (which were monitored because of their importance in the food chain) had also been analyzed but were below detection limits.

The elemental composition of plants varied with the organic wastes and the rates of application. Fly ash/waste mixtures clearly resulted in increased accumulation of most of the elements analyzed (N, P, B, Cu and Zn) in plant tissues. B was accumulated in plants to phytotoxic levels. Plant concentrations showed positive correlation with extractable B contents in waste amended ash (Schwab *et al.*, 1991). The phytotoxic effects of B, Zn or other mineral salts to various crops when grown on soils treated with organic compost and fly ash amended compost have been reported (Sajwan *et al.*, 1995 and Sajwan, 1996).

Microorganisms play an important role in soil fertility and plant growth. The native soil microbial populations are responsible for organic decomposition and the cycling of nutrients such as C, N, S and P (Wong and Wong, 1986). Fly ash leaving the furnace is sterile but the bacterial populations after one year of disposal were one tenth to one hundredth of the number found in an average soil though the microbial biomass mainly concentrated on ash surface (Rippon and Wood, 1975). Application of organic wastes could serve to increase microbial biomass and enzyme activities in ash apart from increasing organic C and nutrient contents. Much work has been done on the effects of fly ash or fly ash-sludge mixture on soil microbial activities (Arthur *et al.*, 1984; Wong and Wong, 1986; Pichtel, 1990; Pichtel and Hayes, 1990; Wong *et al.*, 1995) but few studies have been done on the changes in microbial population and diversity in waste amended ash and the mineralization of organic nitrogen by the action of microorganisms.

In a preliminary pot trial, fly ash was mixed the various waste materials at different rates. No plant growth was observed in pots containing ash collected from the lagoon. This was consistent with the findings in Chapters 3 and 4 that no plant growth was obtained on lagooned fly ash, despite the addition of fertilizers or organic amendments, unless the high salt and/or B contents are reduced by leaching. Plant growth on amended ash was only feasible when B was leached to about 10 μg/g by flooding (Rippon and Wood, 1975). Plant growth could then be increased by the addition of waste materials. To reduce the inhibitory effects of salts by leaching has been widely used in saline soil and some salt affected. The value of organic wastes for reclaiming spent shale has been evaluated with and without leaching (Williams and Packer, 1979). Although the adverse salt effect could be partly overcome by adding wastes, organic amendments were more effective in supporting better growth and yield of wheatgrass on the spent shale when excessive salts were removed by leaching. Leaching of amended fly ash can also reduce concentrations of trace elements, which further enhance plant growth. However, what is important in creating a successful self-sustaining ecosystem on wasteland is to overcome all the underlying problems of the original site at the outset, whether they are physical, nutritional or toxicity (Bradshaw, 1988). If any of these problems are only partially treated, they will reappear in later stages, leading to revegetation failure.

5.4 **CONCLUSIONS**

Application of organic wastes to pre-leached fly ash can enhance plant growth, in a descending order of (dry weight production) 100 SMC > 50 SS, 50 PMC > 50 SMC, 100 PMC > 100 SS, 50 HMC, 100 HMC. The foliar N and P contents also increased as compared to those from unamended ash. However, the inhibitory effects of waste amended ash were reflected by the phytotoxic symptoms on leaf and lower yield when compared with plants grown on soil. Inhibitory factors were B and salts, and less probably Cu and Zn. Applying organic wastes as amendments coupled with pre-leaching of fly ash seems to be beneficial in terms of nutrient status, physical structure and plant growth. Such amendments could accelerate the development of a self-sustaining ecosystem on an ash lagoon.

Chapter 6 **GENERAL CONCLUSIONS**

Fly ash on the Tsang Tsui lagoon is compact with a high surface penetration resistance. It is alkaline, deficient in plant nutrients (especially N and P) and organic matter. The soluble salt and B contents are very high, exceeding levels of plant toxicity. Among them, high contents of salts and B seem to be the major limiting factors to plant growth. Organic matter has started to accumulate on the ash surface. Soluble salts (measured as electrical conductivity) decline from the surface downward which would be due to upward movement of salts during evaporation. The plant species found on the fly ash lagoon were mostly halophytes, reflecting the saline property of fly ash lagoon. Of the twelve plant species found growing on the lagoons, *Leptochloa fusca*, *Fimbristylis polytrichoides* and *Tamarix chinensis* ranked the top three in terms of importance value (a summation of relative density, relative dominance and relative frequency). Vegetation is likely to be found on cracks on the fly ash lagoon. Ripping is a possible way to provide more microhabitats for germination and growth of plants. Application of rocks and/or barks could serve this purpose.

No plant growth was observed in ash in pot trials unless the ash was washed (to reduce the salts and elemental contents) suggesting that toxicities (probably due to high soluble salts and B) were the major plant growth limiting factor(s). After washing, plant growth was enhanced by the subsequent addition of plant nutrients; N and P deficiencies would then be growth limiting.

Selection of tolerant species for establishment on fly ash lagoon was conducted in a greenhouse pot trial. No germination and growth of grass species was observed. Of the twenty five tree species tested, five were survived on lagooned fly ash. They are *Melaleuca leucadendron*, *Leucaena leucocephala*, *Casuarina equisetifolia*, *Cerbera manghas* and *Hibiscus tiliaceus* which are all halophytic plants. Thus, to revegetate the lagooned fly ash simply by using salt tolerant plants may help but not necessarily be promising. However, they should be considered first (especially for the legume and N-fixing species) in choosing plant species for revegetaion of the ash lagoon if the edaphological properties of ash are improved by treatments such as leaching or addition of organic amendments.

It was demonstrated that leaching could effectively remove soluble salts and B in fly ash as well as promoting growth of the test plant *Lolium perenne*. By applying about 200 - 400 mm water, soluble salts began to level off in concentration along the ash profile while B continues to decline slowly even after 800 mm of leaching water added. The slower removal rate of B would control the volume required for successful leaching and revegetation on fly ash lagoon. Artificial irrigation on the fly ash lagoon may not be necessary since the average annual rainfall in Hong Kong (about 2300 mm) is enough to leach most of the salts and B out of the rooting zone. What is needed to install on the ash lagoon would be a drainage system which could enhance the leaching process.

Solely applying organic wastes on lagooned fly ash cannot promote any growth of *Lolium perenne*. However, once lagooned fly ash has been leached, the addition of organic materials can promote plant growth relative to ash control. The dry weight production, in descending order, was 100 SMC > 50 SS, 50 PMC > 50 SMC, 100 PMC > 100 SS, 50 HMC, 100 HMC. Application of 50 SS, 50 PMC, 100 SS and 100 PMC can increase the foliar N content as compared to ash control while 50 SS, 50 SMC, 100 SS and 100 SMC can increase foliar P content. Applying organic wastes as amendments coupled with pre-leaching of fly ash seems to be beneficial to substrate nutrient status and plant growth.

Most of the treatments suggested above are not particularly elaborated and expensive except the engineering operations associated with drainage. Since the goal of reclamation must be a self-sustaining ecosystem, to attain this, it requires that all the physical, nutritional and toxicity problems are overcome. If any of these factors are neglected or partially treated (like applying organic amendments on lagooned fly ash without treating the high salt and B contents), the problems will still exist and it would be difficult and extremely expensive to treat the problem again.

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